An Assessment of the Fluvial Geomorphology in the Upper Ouse Catchment

by

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution, and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signed

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22-07-2010 Date

This thesis is an uncorrected text as submitted for examination.

Abstract

It is well known that the construction of dams limits the downstream transportation of sediment and this issue has been the topic research in many alluvial river settings. Less researched however, are the impacts of dams in alpine low sloped rivers, comprised by gravel to boulder sized material. In this study I investigate the composition of sediment downstream of Augusta Dam to the Liawenee Canal off-take on the Ouse River, Central Highlands, Tasmania, where Augusta Dam has been operating for nearly 60 years. I attempt to determine whether the current operation of Augusta Dam is limiting ecological succession between Augusta Dam and the Liawenee Canal off-take. The study area resides wholly within the Tasmanian Wilderness World Heritage Area (TWWHA). Two upstream river reaches that flow into Lake Augusta, the Ouse and James Rivers, were used as reference sites against which to compare the river condition downstream from the dam. Sediment composition was analysed at 24 sites comprising eight sites on the regulated reach and both reference streams. A relatively new and rapid method of determining grain size distribution digitally through the use of photographs of the river bed was utilised in this study. This involved processing digital images of the river-bed substrate collected over a set of 850mm x 850mm quadrats and use of Digital Gravelometer™ software package. Raw data of individual grain sizes were exported, grouped into classes and analysed in SPSS and Primer statistical analysis packages. The results indicated that subtle alterations to the substrate had occurred downstream of Augusta Dam, rather than the expected downstream stripping of fine sediment. These subtle changes included an evening of the sediment classes in the regulated sites so that there was less variability between sites, compared to the high inter-site variability that was observed between the reference sites. Data on measured cross-sections and hydrology, estimate of Manning's n, slope and surface grain size distribution was then input into two different surface based sediment transport equations to determine empirically, what sediment transport was likely to occur within the study area. Rates of sediment transport were determined to be relatively low, but showed a direct relationship with normalised shear stress and a gradient of decreasing downstream sediment transportation. The conclusions drawn from this study were that the sediment alterations that have occurred downstream of Lake Augusta, have done so relatively slowly, and are comparable to other studies in gravel-bed rivers where changes downstream of dams are likely to be more subtle than their alluvial counterparts. After nearly 60 years of operation it is likely that the Ouse River has adjusted and continues to evolve based on current dam releases and is unlikely to return to a natural pre-dam state even if flows were released from the dam specifically targeting downstream sediment movement. Future management of water releases should therefore focus on maintaining the current summer-winter

variations that occur within the present channel that support the adapted ecological processes, such as macroinvertebrates, while meeting the needs of hydro-electricity generation.

Acknowledgments

Quite simply this thesis would not have come together in the timely manner that it has without the dedication of time offered by friends and colleagues. It is therefore important to acknowledge those individuals who provided me with timely field assistance, advice and technical guidance.

I would like to dedicate this thesis to my girlfriend Holly Dean who put up with the long and sometimes wet, but always scrubby field trips and offered her kind words of support during my constantly long nights during the writing up phase of this thesis. You made this hard journey pleasant and I very much enjoyed your field company.

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Chapter 1 Introduction

The regulation of rivers through the construction of dams has imposed changes on river flow and sediment transfer that has continued to instigate change along the regulated reaches of these rivers, downstream of dams, in some cases for over 5000 years (Petts and Gurnell, 2005). Dams are well known to halt the downstream transportation of sediment and in alluvial streams; this has instigated scouring of sediments from the channel bed leading to channel alterations. The geomorphic impacts on many regulated alluvial lowland rivers have been investigated throughout southeast Australia, and indeed Tasmania. However, there has been relatively little research conducted on the impacts of dams in alpine harder-substrate rivers, specifically gravel-cobble-boulder based rivers.

Lake Augusta is comprised of two alpine lakes that were enlarged to form one larger lake by damming the headwaters of the Ouse River and James Rivers, gravel-cobble-boulder rivers, for the generation of hydro-electricity in the early 1950s. This development lies within a much broader area that has since been recognised as having outstanding natural and cultural values and has been incorporated into the Tasmanian Wilderness World Heritage Area (TWWHA). As custodian of an asset in the WHA, Hydro Tasmania commissioned a report (Massey, 2007) to investigate the health of the Ouse River and its tributary the Shannon River to assess whether environmental management practices could be improved along the catchment.

The report identified the Ouse River downstream of Lake Augusta to the Liawenee Canal off-take as 'hydrologically hostile' and with limited potential for ecological succession on the basis of current flow releases from dam operations (Massey, 2007). Brierley and Fryirs (2005) state that "…*inorganic particles (silt, sand, gravel, and cobble), are primary determinants of the abundance and diversity of many aquatic organisms, especially macroinvertebrates, macrophytes, and algae*". To expand the knowledge of the geomorphological impacts associated with dam operations in alpine areas, particularly gravel-cobble-boulder based rivers; this study was devised to look at these limits to ecological succession. It focused on the sediment composition in the Ouse River, downstream of Lake Augusta.

1.1 Aim

The purpose of this study was to determine the sediment composition within the Ouse River downstream of Lake Augusta to the Liawenee Canal off-take in the Central Highlands of Tasmania, Australia, in an attempt to determine any limits that present river management problems for ecological succession. This was investigated by examining the current sediment composition downstream of Lake Augusta to Liawenee Canal off-take and, the mechanisms that transport sediment and then comparing the sediment composition of regulated reaches with unregulated (reference) reaches of tributary streams of comparable character that flow into Lake Augusta. These data were then compared to obtain insight into the sediment differences, such as sediment sorting and stripping, between regulated and unregulated river reaches. A review of current ecological and geomorphological literature supported this research.

1.1.1 Research Approach

Chapter 1 of this thesis provides an introduction to the purpose of the current study and research aims. Chapter 2 then reviews current ecological and geomorphological literature to identify that relationships between the physical and biological processes are interlinked and do not operate as separate entities, despite often being studied separately. An overview of the study area is provided in Chapter 3, which identifies the broader study area, the natural processes through which the present environmental setting evolved and the anthropogenic influences that have occurred since European habitation. The process adopted for investigating the fluvial geomorphology and more specifically the sediment composition with the study area is explained in Chapter 4, which outlines the qualitative and quantitative research methods employed. Chapter 5 displays and explains the results that were obtained from the field and desktop research. These results are further discussed in Chapter 6 in which the results obtained in this study relate to previously-reported research on other regulated rivers. Chapter 7 concludes this study by summarising the key messages from the discussion in the context of the original aim and purpose of this research.

Chapter 2 Literature Review

This section reviews relevant current and past literature on stream and riparian ecology, hydrology, environmental flow methodologies, fluvial geomorphology and more specifically methods in measuring bedload and bedload discharge. The intended focus is on the underlying or dominant role that geomorphology plays as a functional linkage between the biotic and abiotic environment, particularly with reference to other ecological disciplines, a linkage that was first drawn to prominence in the scientific literature by Vannote et al. (1980), a significant publication in its time. All too often linkages between geomorphology and ecology (water quality and ecological relationships) are ignored, ironically, as typically in rehabilitation projects there is an attempt to manipulate the physical structure (Brierley et al., 2010).

2.1 Aquatic Fauna

There are a range of geomorphic habitats within a river that support different biological species. Church (1992) recognised that intermediate sized channels provide the optimum habitat for spawning and rearing of fishes. It is the riffles within a stream that provide spawning sites amongst the clean gravels, while the more sheltered side channels and pools provide rearing habitat (Church, 1992). In forested environments intermediate channels may be dominated by over-hanging riparian vegetation, which provides shelter, a source of dropping food and stability for the stream bank (1992). A habitat assessment for fish species will typically require a refined assessment of the water flow velocity and depth distributions, requiring a complete disaggregated bivariate distribution of these parameters throughout the reach (Church, 1992). Habitat assessment for fish species, therefore, may require detailed analysis of biological and geomorphological parameters. Recently, there has been a growing trend towards the use of rapid assessment methods due to a common need to gather information quickly and in a cost effective manner (Metzeling et al., 2003). Macroinvertebrates are a widely used indicator for the condition of aquatic ecosystems since they form an important part of the food chain in aquatic ecosystems, are easy to study, and are useful for monitoring a range of river management issues (Gordon et al. 2004).

2.1.1 Macroinvertebrates

Ecological methods in stream assessments have often focused on macroinvertebrates for quantitative studies and rapid assessment methods as:

- they are likely to be present in all study areas;

- they play a central roles in stream ecosystems;
- the numbers of species present often reflects environmental stresses;
- variation in family composition and populations indicate subtle impacts, and, behavioural changes can readily be measured and interpreted to derive an indication of community impacts;
- their sedentary nature enables spatial reference of pollutant point sources; and
- their long life cycle compared to other groups can be useful for assessing temporal alterations associated with environmental alterations (Clarke et al., 2008; Gordon et al. 2004; Metzeling et al., 2003; Davis et al., 1999)

Macroinvertebrates are sensitive to shifts in flow regime, and are therefore useful bio-indicators for assessing aquatic ecosystem health (Lloyd *et al.* 2003; Smith, 2004). A shift from slow to fast flow in a river, such as might result from forest clearing, often results in a macroinvertebrate community composition shift immediately following the initial clearance (Davies et al., 2005). Typically, macroinvertebrate sampling is undertaken in pool and riffle habitats along river sections and will reveal macroinvertebrate response to regulated flow regimes, including the shift in community composition (Rose and Bevitt, 2003).

Macroinvertebrates are both abundant and diverse and their size enables them to be retained in a <500 um sieve, ensuring that representative numbers can be collected (Smith, 2004). The inundation timing and duration will affect both the macroinvertebrate and zooplankton community composition by affecting the egg bank at the very beginning of the life cycle, for macroinvertebrates, and reducing abundance and altering the composition in zooplankton (Lloyd et al. 2003). Macroinvertebrates form an important link between the hydrology, geomorphology, vegetation and water quality; since all these factors interact in was that alter macroinvertebrate communities.

2.2 Aquatic and Riparian Vegetation

2.2.1 Vegetation Removal

The study of forestry operations often provides insight into the impacts associated with catchment clearing, particularly from the upper tributary slopes. One particular study conducted in eastern Tasmania looked at stream-bed transport resulting from forestry operations (Crooks, 1982). In this study, it was found that clear-felling operations in one catchment in particular were sub-standard and the Forestry Commission 'Guidelines for Logging and Control of

Erosion' had been completely disregarded (Crooks, 1982). In the winter of 1980, 50 mm of rain resulted in 8.2 kg of sediment being retained in a bedload trap, substantially more than the same event mobilised in neighbouring catchments. There was little doubt that the sub-standard harvesting practices led to substantial increases in bedload transport (Crooks, 1982). The study showed that sediment mobilisation could continue for longer than two years in catchments that have been logged (Crooks, 1982). Recent similar studies in the headwaters of the South Esk River, assessed the changes in stream morphology that resulted from logging operations and identified that changes in granite streams are still apparent after 15 years as the river still adjusts to the disturbance (Davies et al., 2005b). These studies indentify the lengthy time for adjustments in the morphology of a headwater river impacted by vegetation removal.

A study of the Cann River in East Gippsland Victoria has shown that the clearing of riparian vegetation, coupled with a de-snagging program, led to catastrophic changes in river metamorphosis (Brierley and Fryirs, 2005). This study found that the initial vegetation clearance that occurred prior to 1919, and the de-snagging program completed by 1971, were primary causes of threshold conditions being exceeded. This led to a 700% increase in channel capacity, a 360% increase in channel depth, a 240% increase in channel slope and a300% increase in bedload transport (Brierley and Fryirs, 2005). As a consequence of these changes the main channel became decoupled from the surrounding floodplains, because the river channel attained the capacity to transport the majority of flow without engaging the associated floodplains (Brierley and Fryirs, 2005).

Logging coupe roads form part of forest clearing operations and are a potential source of sediment linked to vegetation clearance. Where landslides are caused from the construction of a logging road they can produce up to 45 times the volume of sediment that is released naturally from a mature forest (Brierley and Fryirs, 2005). Conversely unlogged catchments tended to yield very low quantities of sediment under all but the most extreme of rainfall conditions (Crooks, 1982).

2.2.2 The Role of Aquatic and Riparian Vegetation

Riparian systems are important because they have an intimate connection with in-stream systems, acting as a template for riparian species distribution and being sensitive indicators of environmental change (Gordon et al., 2004; Evans, 2003). Riparian vegetation benefits river-bank stability through tree roots binding soil within the bank, and may also reduce bank erosion, since the leaves and stems that fall on the banks protect them from sub-aerial processes and scour (Church, 1992; Abernethy and Bresnehan, 2001).

River ecosystems typically have an active channel within which vegetation will typically be restricted to herbs and species adapted to extended periods of inundation (Church, 1992). Vegetation creates roughness along the steam banks and bed as does the sediment within the stream (Brierley and Fryirs, 2005). Sediment, particularly within headwater streams, that becomes mobilised by floods may induce scouring, depositing sediment along channels downstream, thereby damaging riparian vegetation (Gomi, Sidle and Richardson, 2002). However, Brierley and Fryirs (2005) have noted that in a natural state even the most major floods are unable to bring about metamorphosis, such that a flood would remove vegetation and thereby allow a threshold to be passed. Rather, the inherent roughness caused by the vegetation is sufficient that in natural systems with intact riparian landscapes, thresholds for geomorphic change are virtually unattainable by major floods.

Riparian habitats support high levels of biodiversity, are critical in maintaining bank stability and the spiralling of nutrients through riparian and aquatic ecosystems (Brierley and Fryirs, 2005; Jansen et al., 2005). One of the biggest issues leading to extensive loss of ecological condition in riparian areas in Australia is stock access to waterways where stock congregate for shade, drinking water and food (Jansen et al., 2005). However, even intensive disturbance will not necessarily eliminate all vegetation from such sites due to the moisture tolerance of certain riparian zone species (Davies et al., 2005b).

2.3 Hydrology

One distinction between regulated flows and natural stream systems relates to flow variability. In a natural system, river discharge varies in times scales of hours, days, seasons, years, decades and longer (Arthington, 2002). The natural flow regime can therefore be summarised as containing characteristic patterns of flow magnitude, frequency, duration, timing and variability (Poff et. al*.*, 1997). Natural flow influences several interrelated mechanisms that operate over differing spatial and temporal scales and states. There are four principle factors relating to flow regimes that guide aquatic biodiversity: lateral and longitudinal connectivity; channel form and habitat complexity and patch disturbance and how they affect biotic diversity; life history patterns – spawning and recruitment; and natural regimes discourage invasions (Gordon et al., 2004).

The variables effecting flow influence the complexity within river channels, such as the structure of aquatic habitat, food availability, riffle and pool habitats and the link between channel and floodplain ecology. The main driver of ecological processes in rivers and their related floodplains is the temporal associations of rainfall and runoff (Arthington, 2002). The movement of sediment within a river channel is strongly influenced by the hydrological cycle and the ratio of sediment entering the system compared to sediment transported from the river (Leopold, Wolman and Miller, 1992).

All flow within a river is ultimately derived from precipitation; however, it may be delivered from surface water, soil water and ground water (Poff et al., 1997). The life cycle of many aquatic organisms is linked to the timing and frequency of particular flow and flood events. Low flows typically favour breeding conditions for small fish, while higher flows allow organisms to migrate into floodplain habitat. Similarly, the speed with which the water rises and retreats is important because certain species can gain shelter in the streambed or follow retreating floodplain waters back into the main channel (Arthington, 2002).

The pathways through which water is delivered and the supply of water are governed by the local climate, geology type, topography, soils and vegetation (Poff et al., 1997). The measurement of flows by hydrologists is typically undertaken, in basin hydrology, to determine a hydrologic budget (Ritter et al, 2002). In any given river channel the velocity and depth is highly variable and, hence, it often requires measurement of flow at perhaps 30 positions across a stream (Leopold et al., 1992).

The most common method for determining flow is the use of a current meter, where a propeller, fixed to a wading rod is lowered into the water column at a given depth relative to water height and electronic pulses are recorded by each revolution of the propeller as water passes through each of the sections across the stream (USGS, 2010). The process of dividing a stream into sections and measuring the total discharge is shown in Figure 2-1. Recent developments have incorporated the use of the Doppler Effect, by way of an Acoustic Doppler, known as Acoustic Doppler Current Profiler (ADCP) (USGS, 2010). The ADCP uses the Doppler Effect to calculate water velocity by sending a sound pulse through the water and measuring the frequency change of the sound pulse, which is reflected back to the ADCP. The change in frequency, or Doppler Shift, that is measured by the ADCP is translated into water velocity (USGS, 2010). While the use of the ADCP is increasing due to the accuracy of the recordings, which are typically in the order of 0.5-1% error (Whiting, 2007), there have been issues with the transmission of the ADCP signal in very clear water (Blake and Packman, 2007;

Nystrom, Oberg and Rehmann, 2002). Additionally, in the very upper and lower profiles of the water column, the signal has not had enough time to travel a sufficient distance to measure reflections from particles in the water column; this causes an additional source of error can be rectified with manufacturer software (Whiting, 2007).

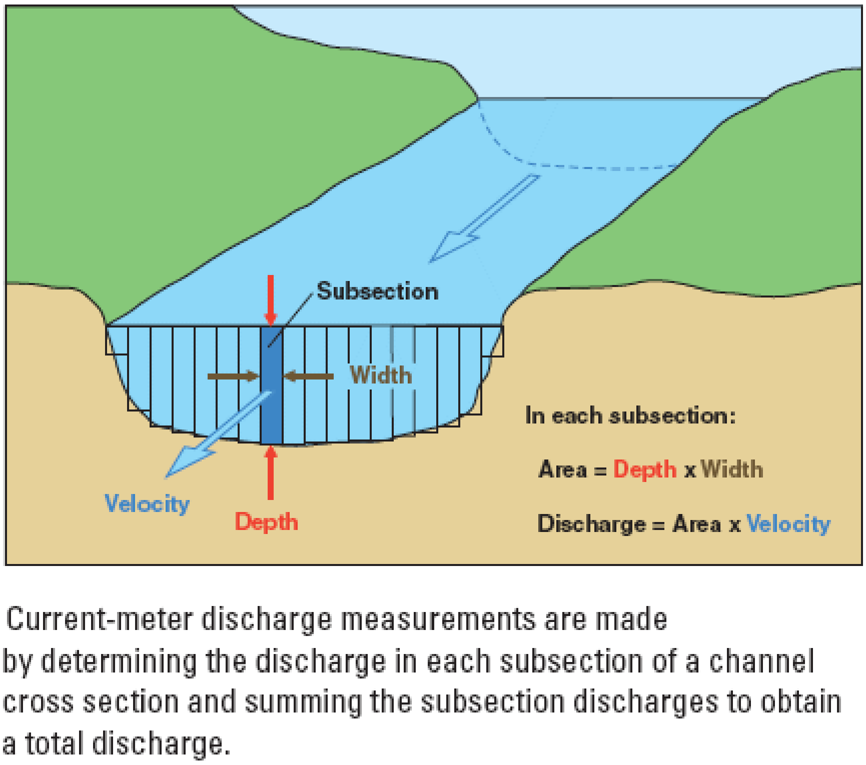


Figure 2-1 Visual representation of the steps in completing a stream gauging (source: USGS, 2010).

2.4 Environmental Flows

An environmental flow can be the release of water to support ecological processes or for human requirements downstream of a physical barrier. Tharme (2003) provides one of the largest and most comprehensive critical reviews of environmental flow methodologies that have been developed worldwide (Gordon et al. 2004; Growns, 1998; Lind, Robson and Mitchell, 2007). Essentially there are four main types of methodologies for assessing environmental flow requirements in riverine systems; hydrological, hydraulic rating, habitat simulation; and, holistic (Gordon et al. 2004; King, Brown and Sabet, 2003; Shang, 2007; Tharme, 2003). Tharme (2003) does mention additional methodologies, these being combinations of the above and other models (Gordon et al. 2004; Shang, 2007) that are regionally specific and not applied on a broad scale.

The four main environmental flow determination methodologies are discussed below and shown visually in Figure 2-2. Reference has been made (where known) to where they have been implemented, the model by which they have been implemented and a brief discussion on the success or application of each. The combination/other methodologies are also briefly mentioned with reference to the above criteria where information is available.

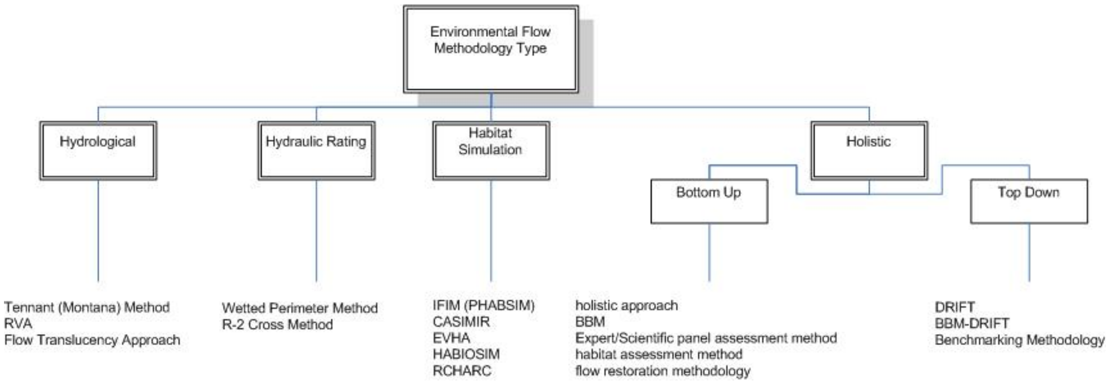


Figure 2-2 The four main Environmental Flow Methodologies with some of the different methods shown below (constructed by author from in text discussions by Gordon et al. 2004 and Tharme, 2003).

2.4.1 Hydrological Methodologies

Often referred to as fixed percentage or look up table methodologies, hydrological methodologies provide the most simplistic way of prescribing environmental flow rules. This is achieved by setting aside a fixed proportion of a rivers flow (often the minimum flow) and allowing this to pass the regulating structure and discharge down river for ecological benefit (Gordon *et al.* 2004; Tharme, 2003). The main benefits of hydrological methodologies are that limits for passing flows can be devised from a desktop review of available stream gauged data via percentage pass-through allowances, with very minimal fieldwork required (Gordon *et al.* 2004). This system is useful for setting preliminary targets at the planning level where large-scale basin-wide flow methodologies are required and controversy over water allocation is limited. The most commonly used hydrological methodology in the world is the Tennant method (after D.L. Tennant), also known as the Montana method (Tharme, 2003), based on where the method was devised. The Tennant method is widely used throughout North America, who account for 26% of all hydrologically based environmental flows in the world (Tharme, 2003).

The Tennant method calculates the required amount of pass-through flows by taking an average of annual flows and considering summer/winter variations. At 10% of the average flow pass-through, fish crowding in (due to riffles being too shallow to pass through), and larger fish migration, both occurred, and water temperature became a limiting factor for survival. In order to maintain satisfactory stream width, depth and velocity, a 30% pass-through of the average flow was found to be required (Gordon *et al.* 2004). Although the Tennant method involved the collection of a significant amount of field data in its development (Tharme, 2003), there has been criticism of this method (Gordon *et al.* 2004). Criticisms surround the methodology's inapplicability to rivers that are morphologically different to those that the method was based upon. Furthermore, the methodology fails to account for daily, seasonal or yearly variations as the development of the method was based upon average flow.

Another Hydrological method, the Range of Variability Approach (RVA) has also become popular due to the inclusion in its flow regime methodology of a broad statistical characterisation of relevant ecological features (Tharme, 2003). Using 32 different indices, the RVA method attempts to categorise differing flow types from long-ranging daily hydrological data. While the RVA method contains some elements required by holistic methodologies, it requires a more rigorous evaluation of the ecological parameters in order for the RVA method to succeed as a holistic flow methodology (Arthington, 1998). Tharme (2003) does acknowledge, however, that the RVA method is not, and was not, designed as a holistic flow methodology.

2.4.2 Hydraulic Rating Methodologies

The study conducted by Tharme (2003) found that there were 23 hydraulic rating methodologies developed worldwide. Hydraulic rating methodologies differ from hydrological methodologies in that the latter use flow duration curves to recommend flows, while the former method uses discharge relationships combined with parameters such as depth, width, velocity and the wetted perimeter (Shang, 2007). The most commonly applied hydraulic rating methodology is the generic wetted perimeter method (Gippel and Stewardson, 1998; Tharme 2003). Typically, a relationship between discharge and wetted perimeter is used to define a minimum environmental flow (Gippel and Stewardson, 1998; Shang, 2007). Two assumptions under-pin the wetted perimeter method, firstly that a rivers integrity is directly related to the quantity of wetted perimeter, particularly in limiting geomorphic features such as riffles and; secondly, the maintenance of these features will ensure overall habitat protection (Tharme, 2003).

The wetted perimeter method is applied by locating transects across representative sections of a river [at riffles] and collecting measurements of depth and velocity over a variety of different flow conditions. The wetted perimeter is plotted against discharge, typically to a logarithmic scale (Gordon *et al.* 2004). The first break in slope of the curve, normally read visually from a plotted graph, indicates the 'minimum optimum' environmental flow (Figure 2-3), as required to stimulate the biota of interest (Gippel and Stewardson, 1998; Gordon *et al.* 2004; Shang, 2007). Issues have arisen in field applications in Australia (Gippel and Stewardson, 1998) where the wetted perimeter method has been applied to rivers of non-uniform nature, and reading the break in the plotted curve indicates flows too low to adequately protect selected biota. This issue was over-come in the above example by applying a critical value to the breaking point in the slope (nominally 1), a practice that has been termed the slope method. The alternative curvature method (used to measure the rate at which the curve turns to determine the break point) was not able to be applied (Gippel and Stewardson, 1998). A more recent study (Shang, 2007) concluded after field applications in China that the curvature method was not good for determining the setting of environmental flows and that while useful as a planning tool, the wetted perimeter methodology fails to provide adequate protection of aquatic ecosystems during critical spawning periods (Gippel and Stewardson, 1998; Shang, 2007).

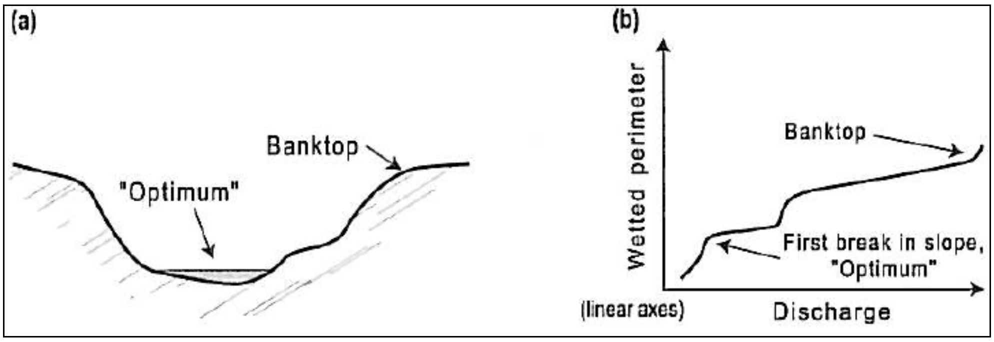


Figure 2-3 Wetted-perimeter method: a) example of a channel cross-section and b) graph showing the wetted perimeter versus flow discharge. The first break in slope represents the minimum 'optimum' water level (Gordon et al. 2004).

There have been few recent advances in the development of hydraulic rating methodologies, rather these methods, played key roles in furthering the development of, and as tools in, habitat stimulation and holistic methodologies. Despite the lack of recent advances, the hydraulic rating method is still in use in North America because the method was developed for local streams. North America has a disproportionately high usage (76%) of hydraulic rating methodologies compared with worldwide use of this methodology. It is likely that hydraulic rating models will decline in use as a sole methodology and in further development, but rather will continue to be used in conjunction with more advanced methods (Tharme, 2003).

2.4.3 Habitat Stimulation Methodologies

Also known as, habitat rating methods, habitat stimulation methods consider the alteration of physical habitat with adjustments in flow regimes. This information is then combined with the target species' preferential habitat, in order to determine available habitat across a variation of river discharges (Gordon *et al.* 2004). Of the 58 recorded habitat stimulation methods devised worldwide, approximately half are *ad hoc* or have only been used several times historically (Tharme, 2003). One of these methodologies, the Instream Flow Incremental Methodology (IFIM) has evolved its beginnings in the late 1970s into the most commonly used environmental flow method in North America and the most widely implemented flow methodology of its type with confirmed usage in 20 countries worldwide (Tharme, 2003).

The basis for the development of the IFIM was to target important fish species (Gordon *et al.* 2004). It has since evolved into a framework that allows the user to assess the impact an altered flow regime has on river ecosystems (Acreman and Dunbar, 2004). IFIM is a tool that can evaluate activities aimed at enhancing river condition. IFIM works by combining a series of concepts, techniques and computer programs in order to link channel morphology, flow characteristics and biological preferences of target biota to alterations to the physical habitat under a modified flow (Gore, Crawford and Addison, 1998). The IFIM considers both the community distribution within habitats by utilising information pertaining to the macro-habitat and the micro-habitat. The latter is used to calculate the Weighted Useable Area (WUA), which forms the core habitat-rating component of the IFIM. The Physical HABitat SIMulation (PHABSIM) is a collection of computer software programmes used to model the WUA, and is the software that 'sits behind' the IFIM (Gordon *et al.* 2004). PHABSIM operates in a Windows computer environment and can be used to predict alterations in velocity, depth and channel resistance in surveyed habitat. The alterations can then be compared with the preferences of the target biota or communities (Gore *et al.* 1998).

The benefits of the IFIM are that large-scale changes or single solutions are not necessarily the result. Rather, 'Incremental' (as IFIM suggests) changes can be modelled to see what effect this has on habitat and biota response and the output from the IFIM provides options allowing the user to evaluate different options depending upon management goals (Gordon *et al.* 2004). The IFIM has been applied to sediment flows and river restoration projects (Tharme, 2003) highlighting that it is not biota-limited in application. Gordon *et al.* (2004) however, note that the method has been criticised for promoting flows too low for sediment mobilisation and too constant in discharge. However, analysis of an Australian application of this type of methodology has confirmed that a range of flow releases has produced diversity in hydraulic habitats with potential benefits to in-stream biota (Dyer and Thoms, 2006).

Further criticisms of the IFIM relate to the considerable time involved in completing a comprehensive study and in generating the computer models. Some additional criticisms have been directed toward omissions and simplifications (Acreman and Dunbar, 2004), assumptions in the computer modelling, macro-habitat components and the lack of ecological predictive capability (Tharme, 2003). Despite all the criticisms of IFIM, it has become a standard method of assessment for large rivers in many North American states where 50% of the world's implemented IFIMs occur. Furthermore, the IFIM has become a legal requirement in some North American states for dam assessment and water abstraction (Acreman and Dunbar, 2004; Gordon *et al.* 2004; Tharme, 2003).

2.4.4 Holistic Methodologies

One of the most diverse group of methodologies, but also the least utilised on a worldwide scale, are the holistic methodologies, which have been implemented only in South Africa, Australia and the United Kingdom (Tharme, 2003). Holistic methodologies were devised from workshops in South Africa from the late 1980s in collaboration with Australian researchers (Acreman and Dunbar, 2004; King *et al.* 2003a; Tharme, 2003). The groundwork for devising holistic methodologies stemmed from recognition by ecologists of the need to partly or fully restore hydrological regimes (Arthington, 2002). Holistic approaches allow aquatic scientists from a range of disciplines to organise flow-related data and information to develop understandings of relationships between the ecosystem and flow requirements and to then collaboratively determine, with team members and key stakeholders, an appropriate environmental flow (King *et al.* 2003a; Gordon *et al.* 2004). There are two main categories incorporating the different types of holistic methodologies, the bottom-up approaches and top-down approaches (Arthington, Brizga and Kennard, 1998; Gordon *et al.* 2004; Tharme, 2003). Each type of approach and the various methods utilised within each method are discussed in the following paragraphs.

Bottom-up methodologies are devised from a 'zero-flows' starting point and built up through the addition of flows for certain ecological requirements from low flows with the addition of freshes through to floods to cover the full suite of possible flow regimes. The methodologies utilised in Australia under the bottom-up approaches include the holistic approach, Building Block Methodology (BBM), Expert/Scientific Panel Assessment Method (E/SPAM), habitat assessment method and flow restoration methodology (Arthington *et al.* 1998). Though it is unclear whether it fits in the bottom-up category of holistic flows, the FLOWS method appears to be another bottom-up holistic method for allocating water releases for a catchment through consideration of biological, geomorphological and physiochemical requirements (SKM *et al.* 2002).

Despite being well documented the BBM is one of only two environmental flow methodologies for which a manual has been written (Arthington *et al.* 1998; Tharme, 2003). The BBM is the most frequently applied method with excess of 15 applications in South Africa alone (Tharme, 2003). Used primarily to construct modified flow regimes the BBM focuses on flow regimes for proposed future development (Arthington *et al.* 1998). This is achieved by utilising relationships between low and high flows and their relevant ecological stresses to compute a time overlay of stress impacts that are linked to a particular flow regime in a river (Tharme, 2003). The strength of the BBM is the ability of the method to incorporate relevant knowledge, which is gathered from low flows (the first building block), channel and habitat maintenance floods (second building block) and spawning/migration freshes (which form the third and final building block, Gordon *et al.* 2004). Although the BBM is the most structured and best documented available methodology for bottom-up holistic approaches (Arthington *et al.* 1998), and can be used in both data-rich and data poor situations (Gordon *et al.* 2004) it has two main shortcomings. Firstly, the method is largely prescriptive, with the outputs being non-negotiable and directed at a single flow regime; and secondly, it does not fully consider the impacts that a river in dynamic equilibrium has on subsistence users, such social impacts form part of the cost for water-resource developments, though they are rarely described (King *et al.* 2003a). While the BBM still forms the basis of most bottom-up methodologies, the BBM led the way for an alternate holistic methodology – DRIFT, which forms part of the top-down approach.

The basis of the top down approach differs fundamentally from the bottom up approach (Figure 2-4), in that a top down approach starts with the river's natural flow conditions (morphological units) and then determines the maximum permissible deviation from this flow (Arthington *et al.* 1998). As mentioned above, DRIFT (Downstream Response to Imposed Flow Transformations) evolved from some of the shortcomings within the BBM. As DRIFT was developed from water resource projects implemented in South Africa, it has incorporated components of previous methodologies, such as BBM (King *et al.* 2003a) and can utilise tools such as the wetted perimeter and PHABSIM in the first of the four components found within the DRIFT method. The DRIFT assessment utilises four modules: biophysical; social; scenario development; and, economic. These modules consider flow requirements for different requirements within the catchment (Acreman and Dunbar, 2004; Gordon *et al.* 2004; King *et al.*

2003a; Tharme, 2003). Module two, social, addresses the Populations At Risk (PAR) by considering the impacts of altered flow regimes on subsistence users of the river resources. The scenario development in the third module incorporates scenarios of altered flow regimes and then assesses how these altered flows would affect subsistence users and the river ecosystem. The economic (fourth) module lists the compensation and mitigation costs associated with the PAR (Gordon *et al.* 2004).

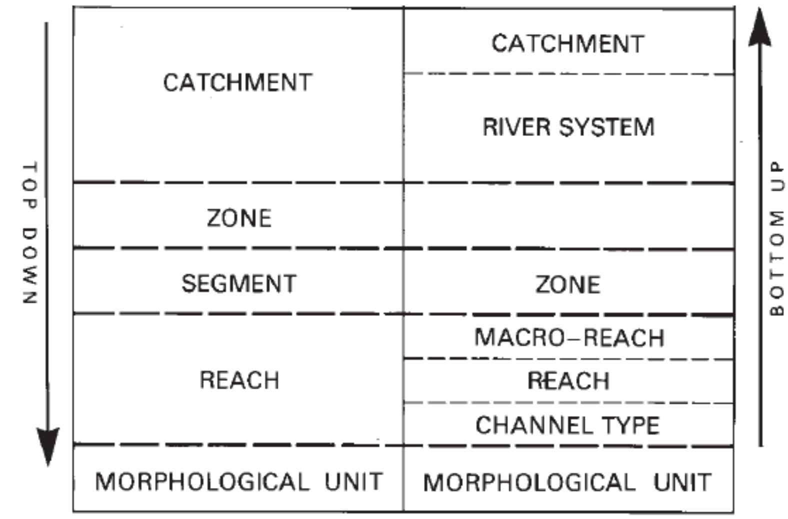


Figure 2-4 Top Down – Bottom Up comparisons in Holistic Methodologies (Dollar, 2000).

The benefit of a methodology such as DRIFT is that it considers traditional ecological and geomorphological links together with the human uses of a river's flow regime (Tharme, 2003). The main disincentives associated with the DRIFT methodology are the lengthy time required for collection of necessary information and the associated information collection costs (Acreman and Dunbar, 2004). Regardless of the criticisms of the DRIFT method there is some consensus (Arthington *et al.* 1998; Gordon *et al.* 2004; Tharme, 2003) that the future holistic methodologies, coined "best-practice frameworks for holistic environmental flow assessments" (Arthington *et al.* 1998) will incorporate a bottom up approach of BBM together with top down approach of DRIFT to have a BBM-DRIFT. This type of approach has been tested in Zimbabwe and aims to link available resources such as data, time and economics as a way to simplify constraints in developing countries where subsistence users are clearly linked to riverine resources (Tharme, 2003).

Other holistic methodologies such as the EPAM and the SPAM represent early applications of holistic approaches in Australia. Such bottom-up applications can be used in-conjunction with other top down methodologies such as the benchmarking methodology, developed by the

Australian Department of Natural Resources (DNR, cited in Arthington *et al.* 1998), which determines environmental flows from the bottom up but then incorporates a top down style, maximum acceptable departure from the natural flow conditions. The benchmarking methodology is typically combined with the habitat assessment method, which utilises key flow statistics or hydrological indicators as descriptive tools to establish the desired geomorphological and ecological conditions. The habitat assessment method has been primarily developed to focus flows for habitat maintenance, setting biological trigger levels and ecological processes (Arthington *et al.* 1998).

It is noteworthy that 94% of all the holistic environmental flows implemented are in the southern hemisphere, with the other 6% being attributed to one implementation in the UK (Tharme, 2003). However as Tharme (2003) acknowledges, there is growing interest in holistic methodologies in other parts of the world and the likely future development of this methodology is in combined bottom up and top down approaches. Further progress in best practice holistic methodologies has involved a two-tiered approach whereby rapid assessment utilising hydraulic rating methodology forms the first tier and a holistic assessment completes the more rigorous second tier (Gordon *et al.* 2004; Tharme, 2003).

2.4.5 Combined Approaches and Other Methodologies

Tharme (2003) identified methodologies that could not be attributed to the categories discussed above. These comprised only a small number [6.8%] of the total number of methodologies. These 13 approaches typically utilise analysis not primarily developed for environmental flow assessment and as such present limited scope for this purpose (Tharme, 2003). The only other main methodology Tharme (2003) identified was the River Invertebrate Prediction and Classification System (RIVPACS). Although not primarily devised for environmental flow assessment, RIVPACS has been utilised for recommending environmental flow releases (EFRs) and may have future use as a tool in various stages of invertebrates and fish flow assessment (Tharme, 2003).

2.5 Fluvial Geomorphology

There is an extensive literature on stream geomorphology that comprises journal articles, books and internet sources, hence, a basic review of geomorphology is not required here; however it is worth reiterating the natural process and pattern of pool-riffle sequences that have been discussed in a wide variety of literature (see for example: Kondolf and Piegay, 2007; Brierley and Fryirs, 2005; Gordon et al. 2004; Leopold et al., 1992; Knighton, 1988;). Church (1992) provides a discussion of the formation of geomorphic units within river systems. In the absence of significant woody debris jams the length of the pool-riffle sequence is typically equivalent to five to seven channel widths; variations from this basic relationship has important implications for habitat quality (Church, 1992). Riffles are typically zones of relatively shallow rapid flow, typically appearing between bends, and they act as zones of sediment transfer that act to steepen the bed (Brierley and Fryirs, 2005; Church, 1992). Scour pools occur adjacent to sediment accumulation areas and are the dominant feature in pool-riffle sequences (Church, 1992). Pools tend to be narrower than riffle zones and act as sediment storage areas. During high flows, pools decrease stream roughness which induces scouring of sediments on the bed. The maintenance of this process is ensured by the velocity reversals that are present during these high flows (Brierley and Fryirs, 2005). This alternating pattern of pool-riffle sequence is often overlaid by more complex interactions with woody debris, bank attached vegetation and the natural flow regime (Church, 1992). The modification of these natural processes through human intervention can significantly alter sediment transport through these systems, upon which, the framework for ecological integrity is built (Brierley and Fryirs, 2005).

2.5.1 The Impact of Dams on Rivers

Dam construction is one of the most obvious, and visible, direct influences affecting the natural flow regime of rivers. The construction of dams and weirs is well known to effectively trap sediment behind the flow barrier and prevent all but the finest sediment from flowing downstream past the reservoir (Poff *et al.* 1997; Brierley and Fryirs, 2005; Bond, 2004; Knighton, 1988). One author (Bond, 2004) found that sediment was particularly restricted by weirs in granite streams and that a downstream reduction in fine material is common when peak flows are sustained. Reducing the sediment available for transportation (sediment starvation), affects the downstream riverine environment. Sediment free water (freshes) released from reservoirs actively erode the fine sediment fraction (~<4mm) from between boulders and cobbles within the river channel (Brierley and Fryirs, 2005; Bond, 2004). The removal of this fine sediment fraction can reduce habitat availability for aquatic species that use sediment for shelter, food source, or for macrophytes that use the interstitial spaces for root development and initial food source (Poff *et al.* 1997; Lloyd, 2003).

In addition to sediment regulation, dams contain and regulate flow events entering the reservoir system, with the total removal of low to medium (and some high) flood events (Figure 2-5) that would otherwise flush sediment through the system (Locher et al. 2002). This lack of flushing events can negatively affect invertebrates and fish communities that are adapted to reproducing during certain life stages. In the absence of flushing events to remove sediment, the eggs and larvae of invertebrates and fish can suffer high mortality rates (Poff *et al.* 1997). However, it is noted that further downstream, the effects of a dam will be diminished (Figure 2-6) due to the increased sediment and hydraulic inputs from tributaries (Knighton, 1984).

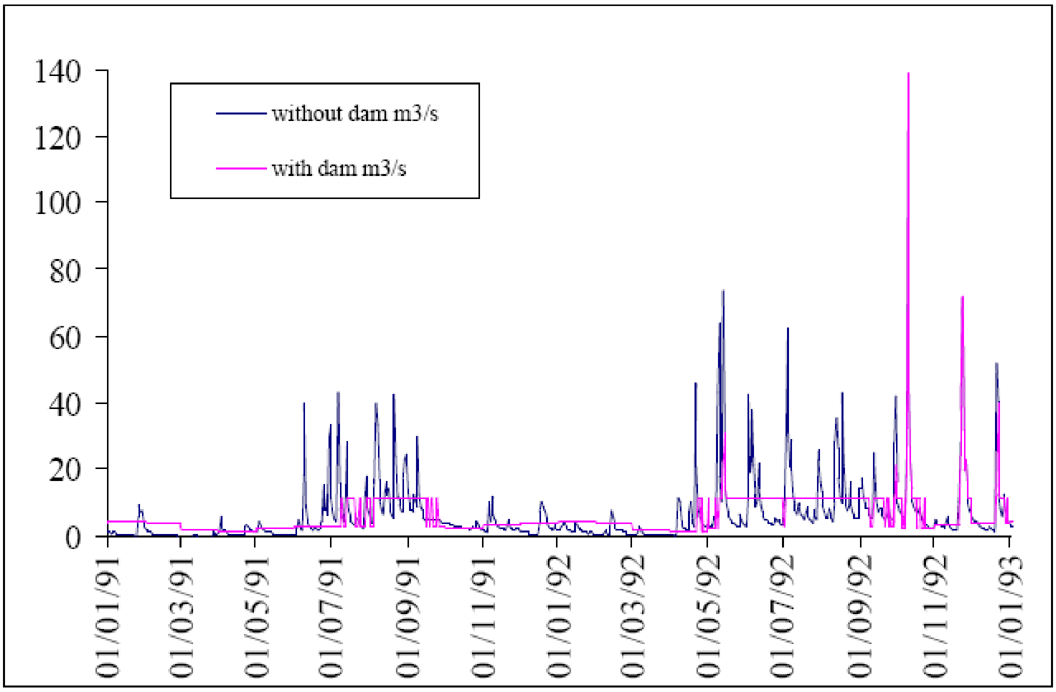


Figure 2-5 Hydrological data from Meander River, Tasmania (Locher et al. 2002), displaying flow data (in cumecs) to illustrate the before and after effects of dam construction on downstream hydrology.

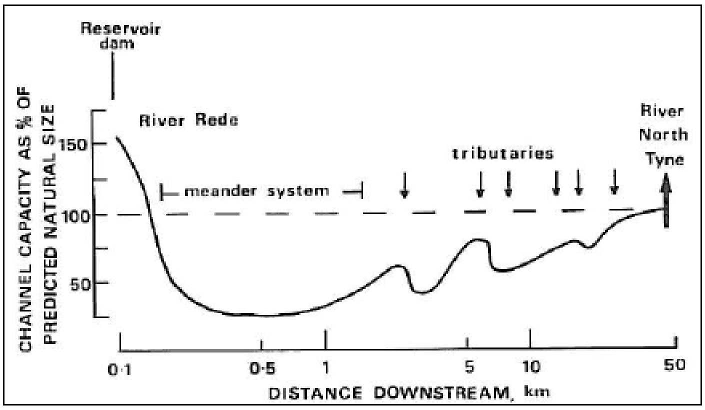


Figure 2-6 Channel capacity variations downstream of Catcleugh reservoir, north east England, illustrating the influence of tributary inflows on the trunk river (Knighton, 1984).

It is not only what the constructed dam controls in terms of disturbing natural hydrology, but how the reservoir is managed operationally that can result in direct impacts occurring downstream. Diverting additional water into a catchment (inter-basin transfers) and flow regulation have both led to channel widening in alluvial sections of the Gordon River in southwest Tasmania (Hydro Tasmania, 2005a). In the Gordon River power station shutdowns result in the drawdown of downstream water levels faster than normal river fluctuation rates (as well as below normal low water levels). Such drawdown events in alluvial settings along the Gordon River induce piping erosion of the river banks. This is caused through variability in ground pore-water pressure due to the alternating wetting (as the power station discharges) and drying (as the power station ramps down). This causes water within the river banks to drain faster than under natural conditions, leading to preferential flow paths becoming established (Locher, *et al.* 2002). The river banks become saturated during the discharge and as the power station has the ability to rapidly reduce river flows saturated banks remain unsupported by the water column in the main channel. Some water will drain from the exposed beds, particularly in porous sandy and loam materials; and such drainage can cause the removal of bank material and increases the potential for bank slumping to occur (pers. obs., Gordon River, southwest Tasmania 2007-2009).

Despite the resupply of some localised sediment through erosion, dams typically starve rivers of sediment. Bedload downstream of dams is then supplied only from downstream tributaries. This bedload input at the confluence of the tributary with the main river channel increases downstream deposition of the main channel (Petts, 1984, in Locher *et al.* 2002). The formation of sediment slugs downstream of tributaries, a phenomenon, known as tributary rejuvenation, occurs due to increased bed-load in the tributaries entering the main river channel during flood events (Knighton, 1984). Flows in the main channel of a regulated river are often lower when downstream tributaries are in flood. This leads to greater flow present in tributaries than in the main river, which causes an increase in the surface water slope from the adjoining tributaries. The increase in slope accelerates river flow and increases to potential for sediment transport, resulting in erosion of the adjoining tributary and leads to a head-cut or nick-point retreat whereby the tributary begins actively eroding while the flow in the main channel incises or armours its bed (Brierley and Fryirs, 2005; Locher *et al.* 2002; Poff *et al.* 1997).

In alluvial catchments bed lowering through incision below a dam is likely; however, where a river downstream of a dam contains a range of particle sizes, fines may be transported, leaving behind larger sediment that cannot be transported due to the reduced river flow. This winnowing of fines leads to the development of an armoured layer which limits the rate of further incision and sediment transport (Leopold, *et al.*, 1992). Once the fine sediment is stripped, the larger gravel-cobble sized material remains in-contact, to form a channel bed matrix known as a framework-supported bed. The opposite of this may result further downstream when material eroded from upstream is deposited. If the proportion of fines and sands (<2 mm) increases to comprise approximately 40 per cent of the bed material, the bed is then characterised as matrix-supported. Bedload transport tends to occur at much greater rates in a matrix-supported bed (Wilcock, Pitlick and Cui, 2009).

2.5.2 Sediment Transport

It is important to understand the different approaches to deriving estimates of total bedload in order to understand the limitations in both equation based and sampling focused bedload transport calculations. Discussion of methods on total catchment yield has intentionally been omitted from this section of the literature review because the current study is focused on bedload transport. To include total catchment yield, this study would need to be expanded to include suspended sediment transport, which is outside the scope and constraints of the current study. However for contextual purposes some discussion is provided below on suspended sediment and total catchment yield.

Material transported by a river can be separated into two distinct categories, namely material travelling as suspended sediment and that travelling as bedload. In suspended sediment transport the load is transported by turbulent flow and eddies that cause an upward movement or flux in the flow. One component of suspended load is sometimes categorised further into 'wash load', being material that remains in suspension and is unrelated to the hydraulic conditions of a river (Leopold, *et al.*, 1992). Suspended load may also be transported in the flow between larger grains in bed sediments. Bedload comprises all coarse sediment unable to be carried by the flow that moves by sliding, rolling or saltating (a bouncing effect) close to the stream bed surface. Bedload continuously interacts with the river bed and may contribute to morphological change in a river or may be absorbed amongst larger grains, limiting morphological influence (Frings, Kleinhans and Vollmer, 2008; Leopold, *et al.*, 1992).

There are a range of reasons as to why sediment within channels is measured. Suspended sediment in large quantities can lead to the development of narrow, deep channels or changes in the stream course and also impact on overbank deposition and smothering the streambed (Fraley, 2004; Rutherfurd, Jerie and Marsh, 1999). Therefore knowledge regarding quantities and concentration assist in determining the rehabilitation potential of a stream or the changes that may result from continued suspended sediment transport. Conversely bedload sediment composition is studied for a variety of reasons. These include determining the framework size and composition of gravels to fine sediment for fish spawning suitability (Kondolf, 1997). Ascertaining roughness is important to determine the formation and location of bars and side-channels in the river for establishment or transportation of vegetation (North Barker and Associates – Ecosystem Services, 2003; Ritter et al., 2002). This in turn can lead to the development of woody debris in rivers (Brierley and Fryirs, 2005) increasing stream complexity, regulating sediment transport, creating physical features (scour pools and channel bars) and providing physical habitat for biota at all levels of the food chain (Brooks et al., 2006).

The composition of the suspended load and bedload that is transported by a river is generally referred to as the total sediment load or yield. Sediment load is recorded as the amount of sediment passing through a cross-section per unit of time (Fraley, 2004) and it influences bed elevation which is dependent on the relationship between sediment transport and supply (de Boer et al, 2003). One of the most widely-used diagrams on sediment supply is that based on Lanes Balance equation, captured by Borland (1960, in Wilcock et al., 2009) who recognised that the relationship between sediment load and river discharge is proportionate to sediment size and slope. As can be seen in Figure 2-7 if the sediment load is increased but the flow remains the same, aggradation will occur on the streambed, while conversely if the water discharge is increased, but the sediment load remains the same, then degradation will occur, lowering the streambed. It is recognised however that bedload contributes least to the total load that a river is able to transport (Brierley and Fryirs, 2005). Schumm (1977, in Brierley and Fryirs, 2005) defines a river as a bedload system when more than 11% of the sediment is transported as bedload.

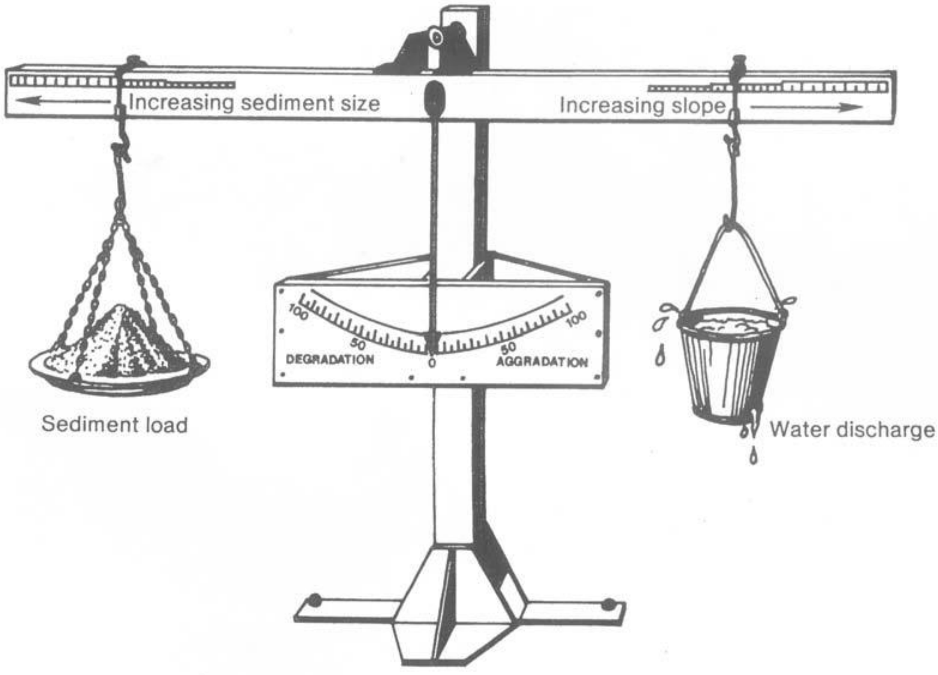


Figure 2-7 Lanes balance equation after Borland (1960, in Wilcock et al., 2009).

Each river and associated tributary will have individual sediment loads that may vary seasonally to deliver a sediment yield per unit of time. Collective yields from each river within a catchment will determine the overall sediment budget (Prosser, et al., 2001a). However, the situation is far more complex than a simple addition, as certain areas will store sediment (such as the storage of suspended sediment on floodplains), while bedload transport may be stochastic with periods of steps and rests (de Boer et al., 2003). These rest periods may result in long residence times for sediment within a river channel (Prosser, *et al.*, 2001b). There is also considerable variability in the distances over which sediment is transported. One study (Prosser, et al., 2001a) found that gully erosion on the Avoca River in western Victoria resulted in short distances of sediment transport; while in a separate granite catchment, headwater incision lead to the transportation of large volumes of sand into a trunk stream. Numerous methods have been employed in the field in order to determine bedload transport rates and total load, with varying success. However, many authors (Raven et al., 2009; Wilcock et al., 2009; Lenzi, 2004; Ritter, Kochel and Miller, 2002; Sear, 1996; Church, 1992; Larone et al., 1992; Leopold et al., 1992; Miyamoto et al., 1992; Hassan, 1990; Heede, 1980) have recognised the difficulty and varying levels of accuracy that are attainable in calculating transport rates due to the issues described above. Variable hydrological regimes and residence times of sediment in the channel and associated floodplains are but a few of the dilemmas in calculating yearly bedload transport rates and quantities with any degree of accuracy.

2.5.3 Bedload Transport Methods

Scour Chains and Beads

One of the more widely used methods to measure scour and fill events is by inserting a scour chain into a stream bed (Laronne et al., 1994; Nawa and Frissell, 1993; Leopold et al., 1992; Hassan, 1990;). The scour chain is driven into the bed vertically to a depth of about 1 m (Laronne et al., 1994). When a flow event occurs in a river system the channel bed may scour, exposing links in the buried chain, and then fill, burying the exposed chain flat in the direction of flow (Larone et al., 1992). The process of scour and fill is shown in Figure 2-8. As the flow increases bedload movement commences then, as the flow recedes, sediment begins to deposit (Nawa and Frissell, 1993; Leopold and Emmett, 1983). However the actual act of installing the scour chain itself is known to cause local disturbance of the bed, involving both compaction and scour around the chain itself. This has prompted revision of field techniques employed in scour chain deployment (Laronne et al., 1994). Relocation of chains has taken up to five days to in some studies; hence, their use can be labour intensive (Laronne et al., 1994). Other studies (Hassan, 1990) that have used scour chains in combination with other methods have indicated that scour can be highly variable, and that this variability may not be recorded by scour chains alone. Alternately, scour holes may develop that are highly localised and therefore, these may not recorded by the scour chains. A different study (Nawa and Frissell, 1993) used sliding beads in a similar fashion to scour chains. Beads have the advantage of being able to be visualised from a distance during higher flows as they become exposed; however, are not as durable or easy to install as scour chains.

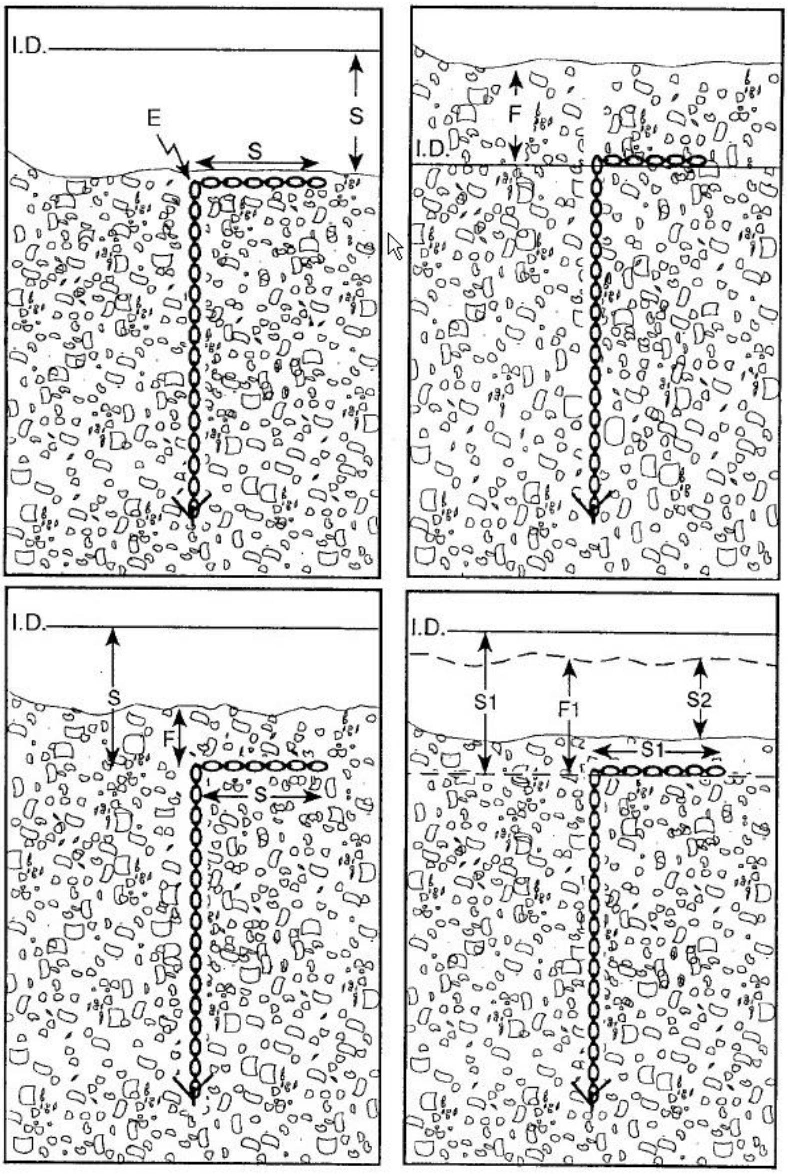


Figure 2-8 Scour chain burial, fill and subsequent scour in a gravel bed stream. ID = Initial Datum, S = scour, E = the depth of initial scour, F = the subsequent fill. The total net scour is measured by S1, and is then followed by fill (F1) and finally scour (S2) (Laronne et al., 1994).

Erosion Pins

A different and frequently used method for determining scour, such as bank erosion studies in alluvial cathcments, is the use of erosion pins (Prosser, Hughes and Rutherfurd, 2000). The erosion pin is a metal rod between 2 and 6 mm in diameter and 0.25 to 0.5 m long (but may be as long as 3 m depending on bank cohesiveness) that is hammered into the ground till solid repose is reached. (Couper, Stott and Maddock, 2002; Koehnken, Locher and Rutherfurd, 2001). A known length is left exposed and sets a benchmark to measure against future change.

Unlike scour chain techniques, the use of erosion pins does not allow recognition of scour *and* subsequent fill, but only the degree of scour *or* fill that has occurred from a flow event. The advantages of erosion pins are that they are simple, cheap and easy to deploy and allow change to be recorded easily (Couper, Stott and Maddock, 2002). There are several known issues with erosion pins however, which include: pin and/or ground movement (shrinking/swelling), the pin can cause localised erosion and vandalism (Couper, Stott and Maddock, 2002). Erosion pins do, however, remain a useful geomorphic tool in current fluvial geomorphic studies (e.g. Noble, 2010).

Marked Cobbles/magnetic tracers/radio tracers

Erosion pins and scour chains are often used in-conjunction with another method for determining bedload rates of movement, namely the use of marked pebbles (Massey, 2009, Hydro Tasmania, 1999; Wilcock, 1997; Laronne et al., 1992a; Hassan, 1990). These have been widely used to assess coarse bedload movement (Lekach and Schick, 1995). Marking of bed material is generally done by selecting grains with a b-axis diameter (thinnest part of the sediment looking from plan view) that represent the 50-84 percentiles within the stream, represented as D_{50} – D_{84}. The larger proportion of the sediment (D_{50} – D_{84}) is typically selected as this is more representative of the pebble to cobble range of the bed material (McNamara and Borden; 2004; Hassan, 1990). Sediments are removed measured, dried, painted and then reinserted into the stream or alternately, painted insitu (Surian et al., 2009a; Hydro Tasmania, 1999; Wilcock, 1997). After a flow event has receded, marked pebbles are relocated and the distance each particle has moved is recorded, comparative to its location before the flow event (Sear, 1996; Laronne et al., 1992a; Hassan, 1990). This method suits the stochastic and spatially variable nature of bedload movement (Schmidt and Ergenzinger, 2006; Wilcock, 1997), which, unlike direct sampling, allows for the mobile portion of bed sediment to be recorded along with the immobile portion (Wilcock, 1997). Some of the main issues with using marked cobbles have been poor percentages of relocation post flow events, and the fact that sampling has been limited to the surface sediments (Wilcock, 1997).

The issue of particle relocation has largely been resolved by the insertion of a magnet into the particle or baking the sediment in an oven to magnetically 'charge' the sediment for later detection with a common metal detector (Lenzi, 2004; Wilcock, 1997; Hassan, 1990; Leeks, 1984). The use of magnetised particles has been shown to allow increased recovery rates by up to 90 percent, although they only identify the resting place for the particles, not which part of the previous flow event moved the particle (Lekach and Schick, 1995).

More recently, radio tracers have been inserted into sediment particles that enable real-time transmission of a particle location in motion (Schmidt and Ergenzinger, 2006; Lekach and Schick, 1995). However, issues of performance and sensitivity in the motion-sensing transmitters implies there are some inaccuracies using this technique and additional tracers are sometimes required to strengthen the results obtained. In this method the strong temporal data obtained from only a few samples may offset the low replications obtained (McNamara and Borden; 2004).

Pit Traps/Bedload Samplers (Helley-Smith)

Methods discussed so far have focused on determining sediment transport from bed elevation alterations and individual grain motion. Other methods in sediment transport include the use of samplers and pit traps. Perhaps the most commonly and continually used bedload sampler is the Helley-Smith sampler (Kondolf, Lisle and Wolman, 2007; Ryan, 2004), the popularity of which is attributable to its simple design. It is a box-like contraption with an opening that faces into the flow and has a mesh netting to collect the sample. Designed primarily for use in fine gravel beds the Helley-Smith sampler (Figure 2-9) is most commonly used in its hand-held form for trapping sediments from 2-10 mm in size (Frayley, 2004). The original version was made from thick cast aluminium and because it weighed 30 kg, it was typically lowered from a cable. It has an opening 76 mm x 76 mm that expands at the exit where a mesh bag 1.9 m2 was attached (Muskatirovic, 2008; Frayley, 2004). The difference in entry to exit of the solid entrance to the sampler creates a pressure-difference that has an expansion ration of 3.2 (Frayley, 2004). The smaller sampler, termed the modified Helley-Smith sampler or US BLH-84, has an expansion ratio of 1.4 and fits more easily into smaller streams, providing some advantages over the original sampler (Kondolf et al., 2007; Frayley, 2004). These advantages include its use, involving less intrusion with the stream flow and less disturbance to bed sediments when lowering the sampler (Frayley, 2004); although problems with the use of the Helley-Smith sampler still encountered.

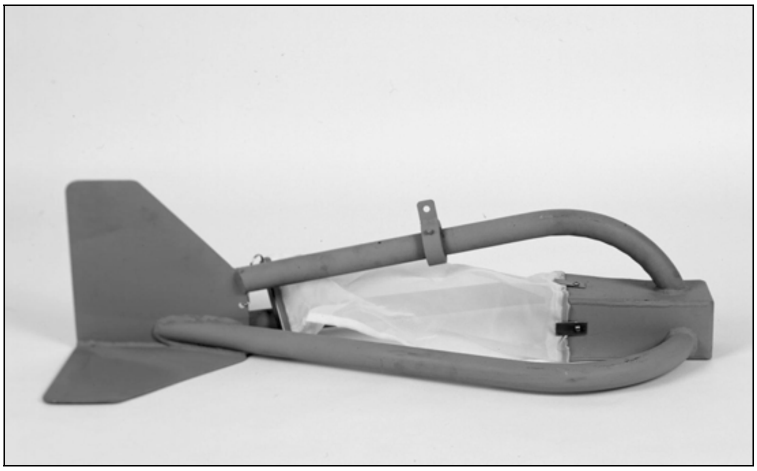


Figure 2-9 The standard Helley-Smith sampler (image source: http://www.rickly.com/ss/bedload.htm#US%20BL-84).

Issues with use of the sampler include the opening not being flush with the direction of flow, the need to keep the base flush with the channel bed, the risk of accidentally scooping sediment when placing the sampler on the stream bed, the potential for capturing some suspended sediment and debris and difficulties encountered in keeping the sampler in the stream for the required ten minutes, often during high flows in deeper areas (Clayton and Pitlick, 2007). Aside from these issues, errors can result if the sample bag is over-filled (>40%) or is clogged by fine debris and sampling only represents a 'grab' in time, that does not necessarily represent the spatial and temporal stochastic alterations within the stream bed (Kondolf et al., 2007). Although the Helley-Smith sampler has limitations, when correctly and consistently used it can provide reliable results (up to 100%), although it often requires four to five transects of a river and the collection of 20-40 samples to obtain representative data from each site (Kondolf et al., 2007). For this reason some users have preferred to install pit or bedload traps.

Bedload traps are pits excavated from the stream bed with a collection device installed that traps material. These are generally considered the most efficient and consistent method of sampling bedload, with efficiencies in the order of 100% (Kondolf et al., 2007; Crooks, 1982). Pit samplers vary from small samplers covered by larger sediment particles to sample fine sediment that fills interstitial spaces (Bond, 2004) through to traps that capture the entire bedload as at Gelignite Creek in south-western Tasmania (Emma Betts, 2008, pers. comms.) and earlier studies in eastern Tasmania (Crooks, 1982). The benefit of bedload traps includes the researcher having the ability to measure the rate at which sediment accumulates after each flood event, providing that the trap is long enough to catch saltating particles. Alternately, a continuous reading can be obtained if the pit trap is fitted with a data logger (Laronne et al., 1992b).

Samples are analysed either volumetrically or by extracting and weighing the sample (Kondolf et al., 2007). Improvement in the traps has meant that samples can be automatically weighed, with the sample being pumped to a weigh station that generates a vortex which ejects the sample after it is weighed (Kondolf et al., 2007) or which records pressure within the sample box via a data logger (Laronne et al., 1992b). Issues around the use of bedload traps include overfilling of the trap by large loads, researchers not checking the trap frequently enough, and poor installation that allows a flood to remove the trap (Kondolf et al., 2007; Crooks, 1982). However, the limiting factor in their use is that bedload traps are both difficult and expensive to install (Kondolf et al., 2007).

Other techniques

Similar to the more advanced bedload traps, pressure pads are sensors fitted to a steel plate that deforms as bedload rolls, slides or saltate over the plate (Rickenmann and McArdell, 2007). The impact records a shock via an electrical impulse that is counted. This method has the benefits of the recording device being flush with the stream bed, low maintenance, continuous monitoring (that records the beginning and cessation of bedload motion so that flow and bedload motion can be linked) and the device giving the researcher the ability to determine bedload from individual flood events (Rickenmann and McArdell, 2007). The disadvantages of this system include the need for calibration, an inability to detect the grain size distribution of the bedload and limited accuracy with short sample periods (hours or days) and small bedload volumes. Pressure pads are useful for recording sediment movement where coarse material may be present causing difficulty with obtaining bedload transport information using other methods (Rickenmann and McArdell, 2007). Similar to pressure pads acoustic sensors have been placed into pipes in the stream bed in one study (Taniguchi et al., 1992) and the vibrations from a particle in motion striking the pipe recorded. However, as with other methods the error margins can be relatively high (30%) in calculating sediment transport (Taniguchi et al., 1992).

Where some particles may saltate over traps or for some other reason fail to be recorded by the method employed, the particle remains unmeasured. One way around such inadvertent failure to measure some sediment particles is to use a weigh station that collects all the sediment and transports it via a conveyor belt for weighing (Ritter, Kochel and Miller, 2002; Leopold et al., 1992). Other systems utilise a bucket for the collection of bedload being mobilised (Miyamoto et al., 1992); however, all of these systems are focused on measurement by weight and recording transport rates.

2.5.4 Surface and Volumetric Sampling Methods

Another set of methods used to sample stream sediments includes volumetric sampling and assessing the composition of the surface sediment in the stream bed. While these types of methods do not provide transport rates some of the methods enable data to be obtained rapidly, and by using empirical transport equations, estimates of expected transport rates can be obtained. It is important to restate though that bedload transport is a relationship between availability and supply of sediment (Kondolf et al., 2007), so equations based on either field or laboratory analysis still need to consider site conditions.

Bulk Sampling

As the name implies, bulk sampling requires the physical collection and analysis of a sample, similar to that involved with use of bedload samplers like the Helley-Smith. Bunte and Abt (2001) identify nine different types of bulk samplers and one hybrid sampler used in volumetric sampling of a stream bed. Some of the more commonly used methods include shovels, mesh-bag scoops, barrel samplers, freeze-corers and backhoes. Typically in bulk sampling no individual stone should exceed 5% of the sample weight (Bunte and Abt, 2001). In one study (Lenzi, 2004) on the Rio Cordon in Italy the maximum diameter was determined to vary from 120 mm to 320 mm, requiring a sampling size from 600 kg to 800 kg; a quite impractical requirement when sampling many small but coarse grained river systems. Additionally this method only records at-a-point in-time sampling and may fail to capture variability in bedload between events (Raven et al., 2009). Bulk sampling tends to retrieve samples that contain more fine sediment as they sample the surface and subsurface sediment populations; while methods aimed at measuring the surface sediments often give coarser grain size distributions. This is due to fine sediment being flushed or winnowed down from the surface layer (Kondolf et al., 2007).

Particle Counts (Wolman Method) and Visual Estimation

Some of the issues associated with the sample size required for bulk sampling led Wolman to develop the pebble count procedure (Kondolf et al., 2007). The pebble count procedure is perhaps most widely utilised method for determining the grain size distribution of surficial gravels. It was first proposed by Wolman (1954 in Kondolf, 1997), and is also referred to as the Wolman Count (Kondolf et al., 2007; Kondolf, 1997) or grid by number sampling (Graham, Reid and Rice, 2005; Graham, Rice and Reid, 2005). Wolman (1954 in Kondolf, 1997) found that by measuring the b-axis and recording a count of 100 stones from a heel-toe walk across the stream bed and the user touching the sediment with one finger (without looking), produced repeatable results for determining the median grain sizes (Fraley, 2004). Other authors have proposed fewer (60-70) stones per sample; however, random error decreases with a sampling size greater than 100 stones (Kondolf, 1997). There have been some issues encountered with sampling that are commonly associated with the finger not being vertical when reaching for a stone, touching two stones at the same time and selecting randomly, failing to avert the eyes when selecting a sample and preservation of shins when attempting to pace evenly across the stream bed (Kondolf et al., 2007; Kondolf, 1997).

Since the work of Wolman is being used extensively by engineers and not only geologists and geomorphologists, guiding principles have been proposed to remove inter-sampler errors (Kondolf, 1997). For example by always, using the right corner of a finger when selecting one grain from a pinch of sediment, such as in a sand patch, the sampling is more accurate and repeatable; also the use of a template may remove inter-sampler error (Kondolf et al., 2007; Graham, et al., 2005a; Fraley, 2004; Bunte and Abt, 2001). The largest source of error however, appears to stem from failing to recognise distinct bed material populations (Kondolf et al., 2007; Kondolf, 1997). A revised Wolman count was proposed by Bevenger and King (1995), termed the 'zig-zag pebble count procedure' that requires measurement of stones while following a zig-zag pattern across the stream every 2.15 m. However, Kondolf (1997) showed through field studies that distinct pockets of sediment sizes may be present within a reach (Figure 2-10) and methods employed that failed to recognise these distinct patches of sediment, such as the zig-zag pebble count procedure, would bias sampling. The result of such an approach is an over-coarsening or over-fining of the sample population and due to the spacing, riffle zones of small streams may only be sampled once. This then discards the main benefits of the original pebble count procedure – accurate and reproducible grain size results for a single population (Kondolf, 1997). To overcome this issue, Kondolf (1997) proposes mapping of sediment populations within the reach to be sampled and measuring a minimum 60-100 stones from each population to ensure that the original rigour of the pebble count procedure is not lost.

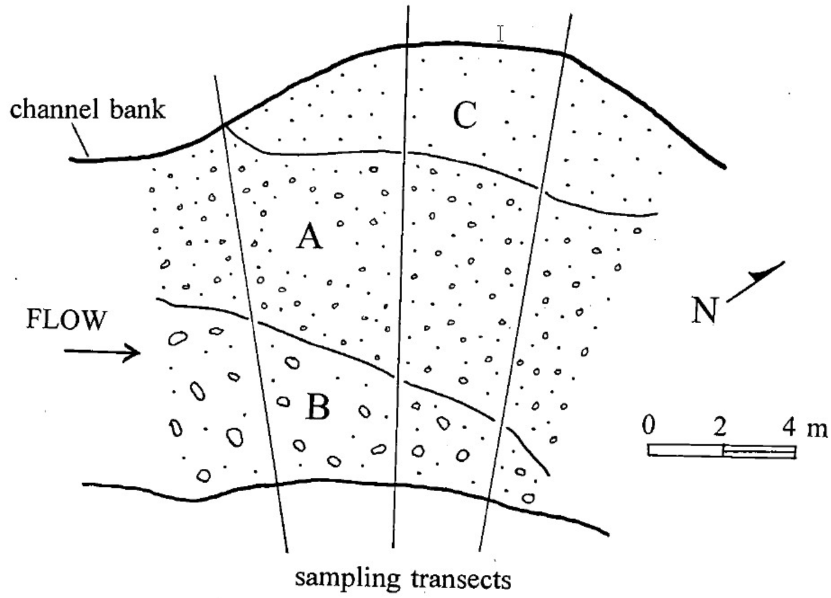


Figure 2-10 visual based method for assessing different sediment populations in a stream bed before particle sampling (Kondolf, 1997).

Photographic Analysis

Despite its accuracy, one of the limiting factors in the use of the pebble count procedure is the time required to collect a sample – often up to 8 hours (Loughborough University Enterprises Limited, 2006). Recent advances in digital granulometry have meant that sampling time can be reduced to one twentieth of the standard time required for a Wolman count (Graham et al., 2005b). Analysis of surface grain size distribution through photographs was first described in literature in 1971 where a grid was used over surface sediments, photographed, measured and then compared to bulk samples (Kondolf et al., 2007). It was found that bulk sampling yielded slightly larger sample sizes, attributable to partial obscuring or shadowing of particles and imbrication (Kondolf et al., 2007; Graham et al., 2005b). More recently, automated software has been developed that produces fast, accurate and repeatable grain size distribution of surficial sediments by analysing the photographs with an algorithm developed to identify particle edges and watershed points, e.g. the top of an individual sediment particle (Graham et al., 2005a; Graham et al., 2005b). However, Kondolf et al. (2007) identify the issue of grain boundary recognition in digital photo processing, which is attributable to three primary sources of error:

- Particle sharing due to bed surface roughness, where larger particles hide the actual size of a neighbouring particle;

- Neighbouring particles being fused together; and
- Incorrect subdividing of large particles into smaller ones, particularly around shaded borders or grouping of smaller particles, particularly in sandy areas.

Errors are not random and it is possible to estimate them through standard regression as a sorting function and percent finer than (e.g. removing particles smaller than 8 mm) (Kondolf et al., 2007). Despite the errors, which have been identified as relatively minor (Graham et al., 2005b), this technique offers many benefits. These include the preservation of the bed surface and the possibility of data collection by operators with limited training and reduced field effort and laboratory time; which can lead to the possibility of increases in sampling rigour (Kondolf et al., 2007; Graham et al., 2005b). The Digital Gravelometer software is one example of software that has been developed for digitally analysing photographs for calculating grain size distribution (Loughborough University Enterprises Limited, 2006). The method involves laying a square grid with metal markers (e.g. wire) protruding into the quadrat from each corner, and then marking the sediment on the ground at the ends of the wire, removing the frame and photographing the bed (Surian et al., 2009a; Graham et al., 2005b). This process is shown in Figure 2-11. One study that has recently collected photos using this method found issues with small plants or vegetal debris being present in the photographs and observed that they required removal prior to photo collection, negating use of the software for fine-grained or densely-vegetated areas (Surian et al., 2009a). Despite this limitation the authors found the software useful for identifying the grain size distribution of the bed sediments, so that exact knowledge of where painted tracers occurred in the grain distribution were obtained (Surian et al., 2009a).

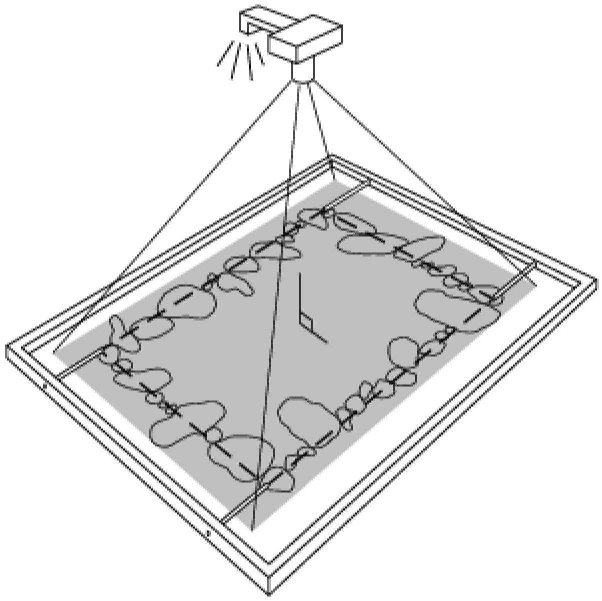


Figure 2-11 Sampling procedure for the collection of digital photos for use in image processing software (Loughborough University Enterprises Limited, 2006).

Aerial Analysis

The development of Geographical Information Systems (GIS) and improvements in the scale of aerial photography have led to improvements in the accuracy of mapping river morphology and geomorphic units. These improvements are continuing with the development of devices such as differential GPS units and improvement with data quality, such as LiDAR data, which allows for rapid surveying of a river channel. The availability of this data allows for volumetric analyses of landform change (Kondolf et al., 2007). The digitising of aerial photographs allows for the mapping of geomorphic units so that geo-rectified images can be used to determine volumetric changes; however, even on imagery at 1:10,000 scale errors can still be in the order of 6 m in accuracy (Surian et al., 2009b). If volumetric rates are to be determined, measuring the temporal changes in an area over time can be used to evaluate the progress of aggradation or erosion (Fraley, 2004). This method is generally better suited to the gross-scale changes that occur and not fine scale or smaller sediment transporting streams. That stated, aerial imagery that spans 50 years can often be obtained that provides information regarding erosion and transportation processes and can be utilised to select field sites or identify sub-catchment alterations; preferably when viewed at scales greater than 1:24,000 (Surian et al., 2009b; Reid and Dunne, 2007; Brierley and Fryirs, 2005; Fraley, 2004).

2.5.5 Calculating Bedload Transport

Due to the many errors associated with sampling bedload for determining transport rates, there have been a number of empirical equations developed in an attempt to calculate transport rates. However caution should be used with the growing number of transport equations as there appears to have been more formulae developed than reliable data sets by which to test them (Hicks and Gomez, 2007).

Some early work by Hjulstrom (1939, in Ritter et al., 2002) focused on developing sediment transport curves relating to current velocity, particle size and process. Figure 2-12 shows the Hjulstrom Curve which shows a simple relationship between flow velocity and particle size. Lane (1955, in Wilcock et al., 2009) attempted build on this by including slope into the equation:

$$Q_sD \sim QS$$

where Qs is sediment supply, D is the grain size of the sediment, Q represents water discharge and S the channel slope (Wilcock et al., 2009; Heede, 1980). This is also shown diagrammatically in Figure 2-7. The limitation in Lane's equation is that it is a qualitative look at sediment transport in a stable channel; often larger quantities of sediment may be carried as wash load or mud-flow may be capable of transporting room-size boulders with relative ease, suggesting lift forces may also be involved (Heede, 1980).

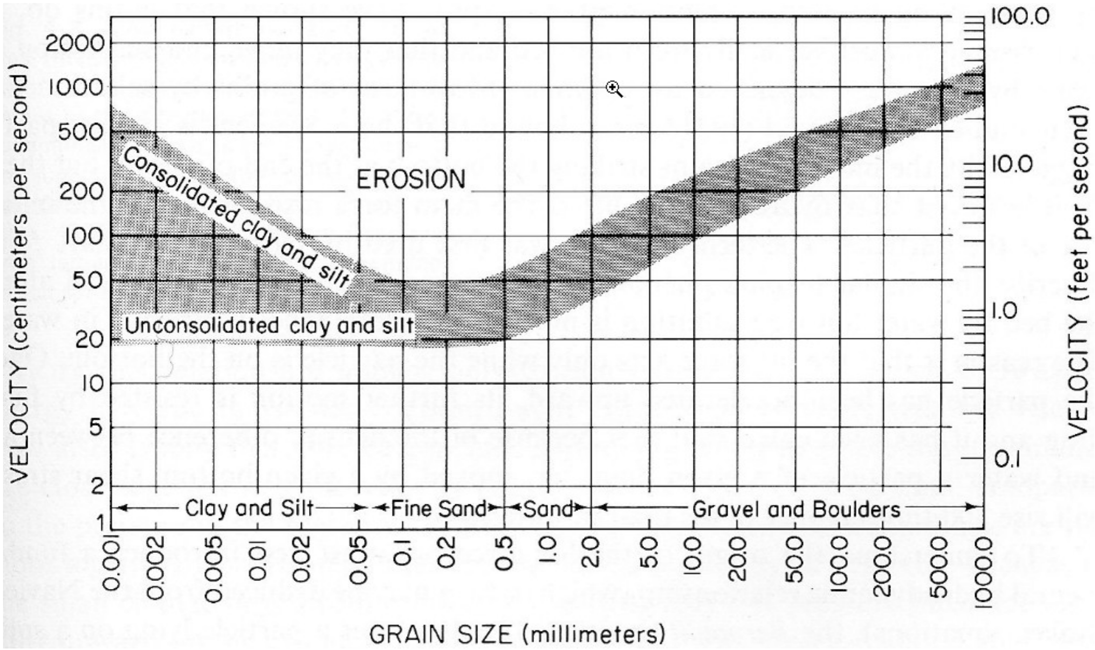


Figure 2-12 The Hjulstrom Curve showing the commencement of particle motion in consolidated and unconsolidated material by flow velocity. Above the shaded area erosion will occur, while below the shaded area deposition occurs (image source: http://faculty.gg.uwyo.edu/neil/teaching/geologypics/hjulstrom.jpg).

To compute bedload transport most equations have, at least partially, incorporated the Du Boys Equation, where transport depends on a coefficient, typically critical bed velocity or critical shear stress (Schwendel, Death and Fuller, 2010; Ritter et al., 2002; Leopold, et al., 1992). The purpose of the critical shear stress equation is to signify the down slope component of the weight exerted on a particle by fluid as motion begins (Ritter et al., 2002; Leopold et al., 1992). The shear stress equation is given as:

$$\tau = \gamma RS$$

where τ represents the shear stress, γ the specific weight of the water, R the hydraulic radius and S the slope. However, often these equations overlook the lifting forces that may be placed upon an individual grain (Ritter et al., 2002).

Some of the earliest work on calculations aimed at total bedload transport were developed from laboratory and flume experiments by Einstein (1950 in Leopold et al., 1992), who devised a complex set of relationships that were referred to as the Einstein bedload function (Hicks and Gomez, 2007; Leopold et al., 1992). This was later modified by Colby and Hembree (1955 in Leopold et al., 1992), referred to as the "modified Einstein computation of sediment discharge".

Since the development of these early equations many others have been developed that focus on differing stream characteristics or output parameters (see for example: Hicks and Gomez, 2007, p445). More recently there have been approaches to target specifically bedload transport rates in gravel-bed rivers and the development of BAGS (Bedload Assessment of Gravel-bed Streams) software is one such example (Wilcock et al., 2009; Pitlick, Cui and Wilcock, 2009). The software has been provided as a Microsoft Excel program using Visual Basic for Applications (VBA) scripting with the outputs stored in spreadsheets (Pitlick et al., 2009). Implementing six different bedload transport equations that have been developed specifically for gravel-bed rivers BAGS software contains both a user manual (Pitlick et al., 2009) and a primer document (Wilcock et al., 2009). The inputs required for the calculations typically include field measurements on channel geometry, reach-average slope and bed material grain size as a minimum (Pitlick et al., 2009). Such software represents current developments in empirical calculations in bedload transport; specifically, gravel-bedded rivers.

Chapter 3 Regional Setting

3.1 Geographic Location

The study area for the Ouse and James Rivers is located approximately 10 km north west of Liawenee, to the west of Great Lake on Tasmania's Central Plateau, occurring at latitude just north of 42° (Figure 3-1). Both the Ouse and James Rivers begin their flow by connecting several small lakes to the north and northwest of Lake Augusta. The northern part of the Ouse River (encompassing the study area) resides completely within the Tasmanian Wilderness World Heritage Area (TWWHA). The specific study area includes the Ouse River from Augusta Dam, past the Liawenee Canal diversion, to 80 m downstream of a gauging station across the Ouse River, some 9 km downstream of Augusta Dam. Particular attention is given to the upper 5km of river reach where tributaries join.

The James River makes up part of the up-stream catchment of Lake Augusta and has similar channel characteristics to the Ouse River. The rivers are suitable for a paired catchment study due to comparable physical characteristics including: slope, aspect, soils, area, vegetation and rainfall (Best et al., 2003). The lower sections of the Ouse River contain large clasts of dolerite that visually appear to be larger comparative to the James River. Field investigations have determined specific sites along both reference rivers that contain similar characteristics making each site suitable as reference sites (see section 4.2.1). The study sites downstream of Lake Augusta were, similar to the reference reaches, identified initially from topographic mapping. Field visits to determine site suitability fine-tuned the location of each site to ensure they were all located where sampling of surface sediments was possible (Figure 3-1).

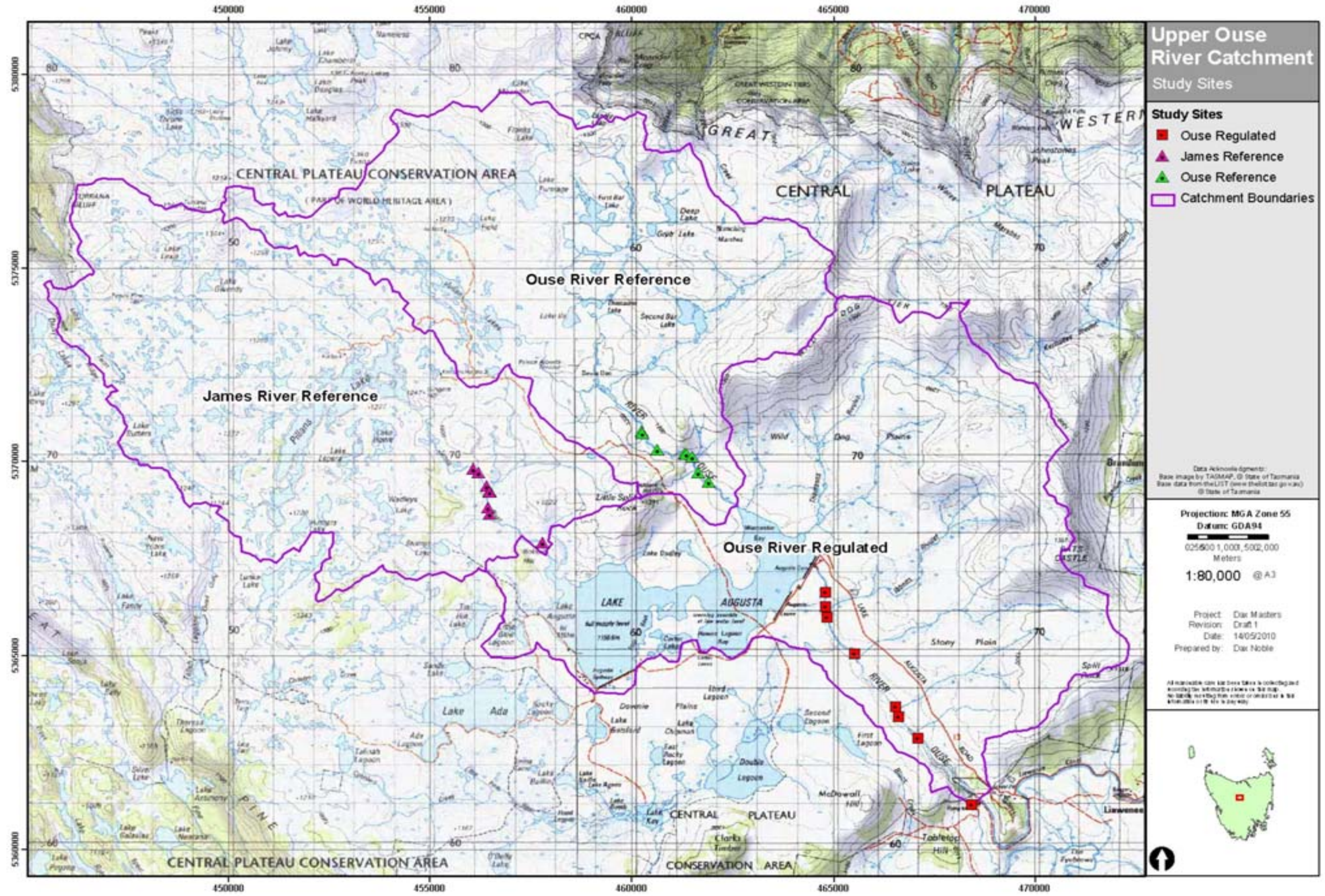


Figure 3-1 The upper Ouse River catchment, showing each of the sub-catchment, James River reference, Ouse River reference and Ouse River regulated and the location of the study sites that reside within each sub-catchment.

3.2 Climate and Rainfall

Climatic averages for Bureau of Meteorology Liawenee Station (096065) is shown in Figure 3-2. Climate data are recorded from the eastern shoreline of Lake Augusta, known as the Augusta east gauging station. The temperature data range from 1985 continuously through to 2003 when recordings of rainfall ceased; the rainfall data runs continuously from 1984 through to current (Figure 3-2). However, past and recent detailed mapping with future forecasts has identified that there is a gradient of higher rainfall further to the north (outside the study area) at Lake Mackenzie with 3000 mm falling that reduces down through the Ouse Catchment at Liawenee to just over 1000 mm (Storey and Comfort, 2007; EIANZ, 2006; Cullen, 1995). Data were sourced from the Lake Gwendy rainfall gauging station, in an attempt to account for this variation. The data were kindly provided with permission of the Team Leader for Water Operations at Hydro Tasmania, Mr Greg Carson in April, 2010. This gauging site was commissioned on 23-04-1992 and continues to record continuous rainfall data at 10 minute intervals to present day; however, due to quality control, only data up until December 2008 has been verified and is presented herein. The results of these rainfall data are provided in Figure 3-3.

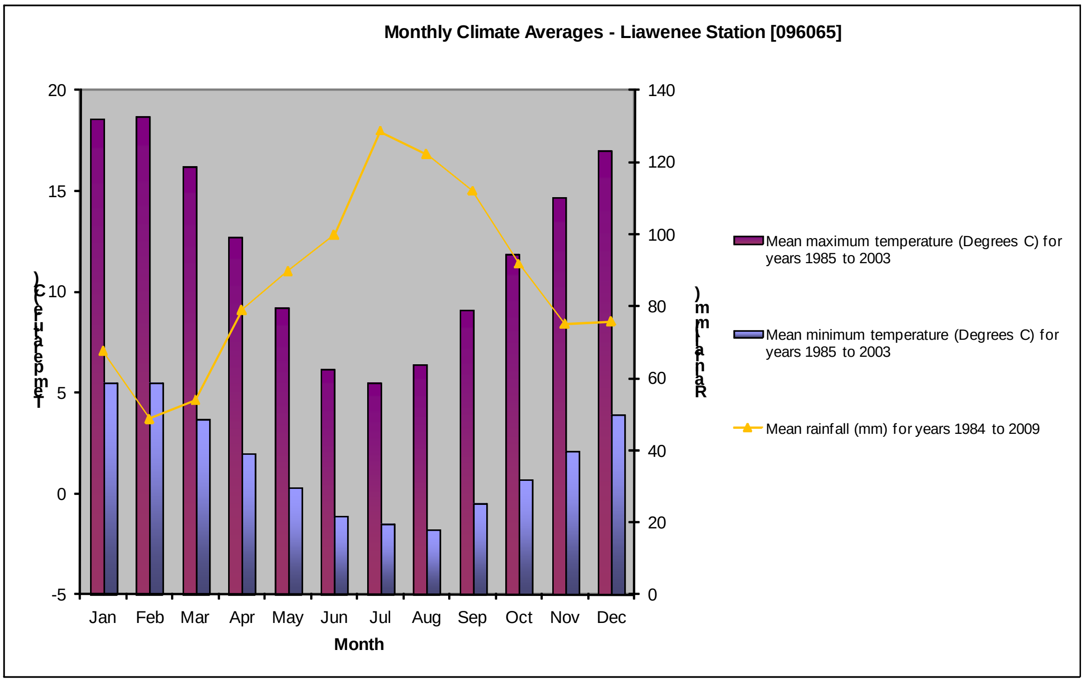


Figure 3-2 Rainfall and Temperature Data from Liawenee

Data were sourced from the Bureau of Meteorology on 10/10/08. The chart displays information contained in the Monthly Climate Statistics for 'Liawenee (COMPARISON)' [096065].

The study area experiences a humid to per-humid cold climate (Cullen, 1995) with an average diurnal temperature range (min -1.8°C in August, max 18.7°C in February), in contrast to the general climate of Tasmania which is temperate maritime (BOM, 2010a; BOM, 2010b). Average annual rainfall varies from 1037.8 mm at the Augusta east station up to 1510 mm at the Lake Gwendy station. As can be seen from Figure 3-2 and Figure 3-3 there is a distinct rainfall gradient between the two stations with the Lake Gwendy Rainfall station recording 50 mm more during peak rainfall months. Furthermore there is a slight shift in the Gwendy rainfall pattern by approximately one month, as Augusta East reaches its maximum monthly average rainfall in July (Figure 3-2) while at Lake Gwendy peak monthly average rainfall occurs in August (Figure 3-3).

Altitude between the gauging stations ranges from 1065 m ASL at the Augusta east gauging station up to 1250 m ASL at the Lake Gwendy rainfall station, 16.5 km to the northwest (Storey and Comfort, 2007). Weather conditions in the study area can be quite bleak with snow, hail, rain or fog at any time of the year; although, snow only persists for months during the winter period from June to August (Storey and Comfort, 2007; Cullen, 1995). Other climatologically relevant data includes minimum ground temperatures, because frost heave combined with either water or wind erosion has been shown to be a significant source of erosion within the study area and greater Central Plateau (Storey and Comfort, 2007; Cullen, 1995). Unfortunately, ground temperature is not recorded at either of the two stations within the broader study area. Wind data is however available and is provided as wind roses below.

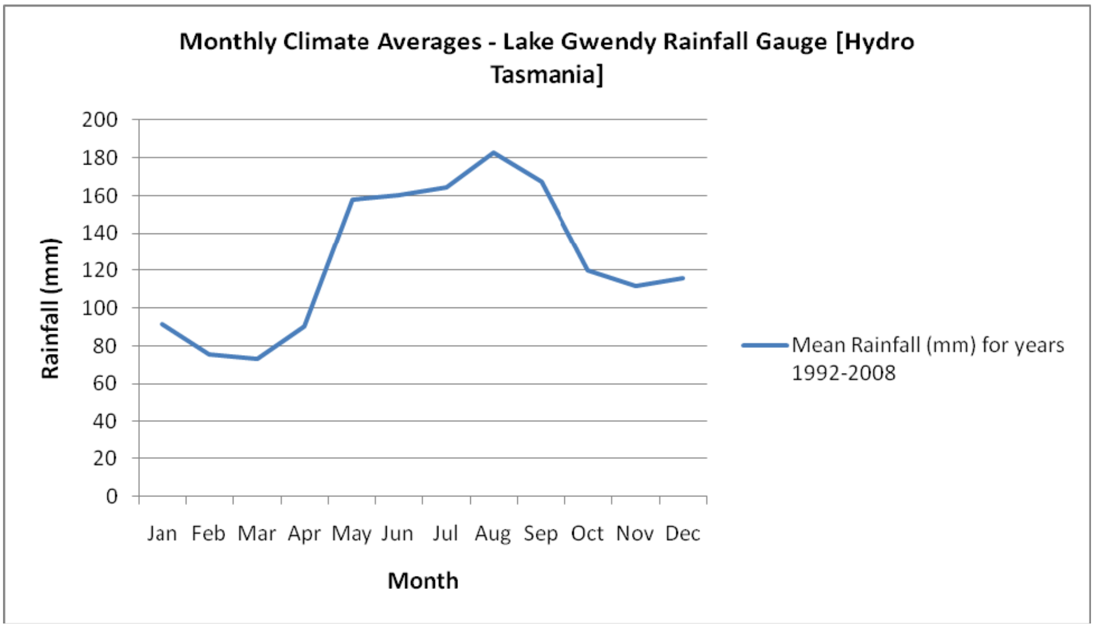
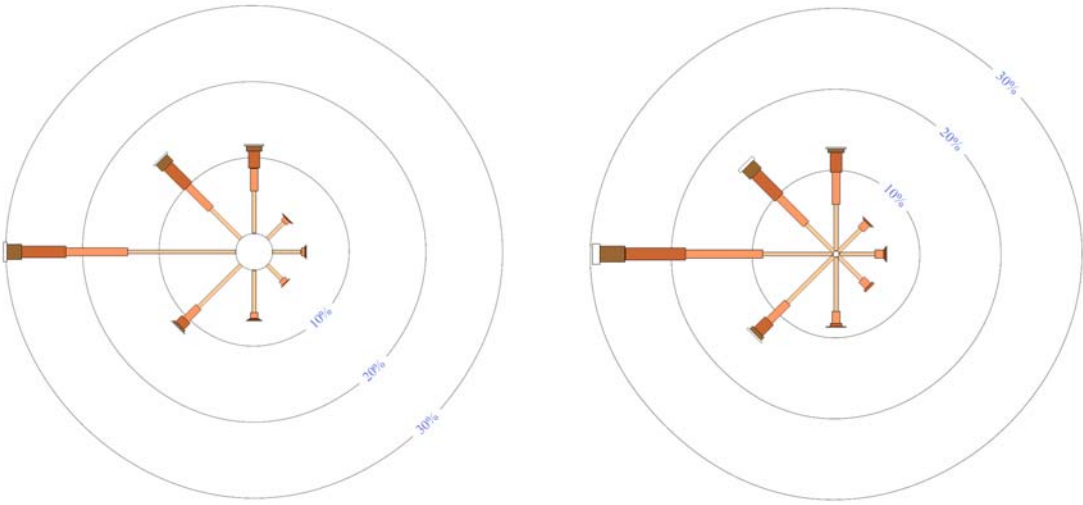


Figure 3-3 Rainfall data from the Gwendy Rainfall Gauging Site

3.2.1 Wind Rose

The dominant direction of prevailing winds is recorded for the study area from the Augusta east station. Wind roses summarise the occurrence of winds at a location, showing their strength, direction and frequency (BOM, 2004). Data are available for 9 am and 3 pm for individual months, seasons and annually (BOM, 2004) recorded between the period 1985, continuously, through to June 2003 (BOM, 2010a). The annual average comparisons for 9 am and 3 pm are shown in Figure 3-4. The data indicate a very dominant westerly wind stream and with each circle representing a 10 km/hr increase in wind speed it can be seen that the annual average wind speed is fairly consistent, recording either slightly over 30 km/hr or slightly under depending on the time of day (BOM, 2004). Combined with frost heave, animal browsing or rain, the wind can contribute to surface erosion within the study area (Storey and Comfort, 2007).



9am 3pm

Figure 3-4 Wind Rose data for the period 1985-2003

3.2.2 Bioregional Setting

The study area occurs within the Tasmanian Central Highlands and occurs on a peri-humid cool to cold high plateau surface that is commonly mantled by Pleistocene glacial and periglacial deposits. Mountain ranges in the upper Ouse River catchment are formed by Jurassic dolerite with some Tertiary basalts. The landscape consists of undulating plains varying in altitude from 900-1200 m. Vegetation ranges from dry sclerophyll woodlands and wet sclerophyll forest on the lower plateau to alpine complexes and coniferous forest patches in fertile, fire protected situations on the higher plateau. Heath, bolster moorland, tussock grassland and mossland occur extensively over vegetated areas. Current land use over the study area is comprised of conservation, recreation and hydro-electric generation storage (Environment Australia, 2000; Pemberton, 1986).

3.3 Past and Current Land Use

Habitation of the study area and more broadly, the Central Plateau, occurred seasonally prior to European settlement by Aboriginal bands (Storey and Comfort, 2007). Aboriginal impacts on land use are likely to have been localised and associated with digging for food, fire for access and are unlikely to have caused any widespread erosion (Storey and Comfort, 2007). The earliest recorded European use of the land was in 1825 for cattle stocking, with the first leases being issued in the 1840s (Cullen, 1995).

As the Plateau proved a useful area for drought relief and was hospitable for summer grazing (which had the added benefit of spelling stock runs at lower altitudes during this season) stocking rates increased on the Central Plateau. Sheep and cattle were grazed in numbers around 350,000 head of sheep and 6000 head of cattle by the late 1800s (Cullen, 1995). Stocking rates were deliberately kept high for wool quality purposes and burning of native vegetation was common practice to remove fibrous and woody material in favour of new 'green-pick'. As the introduced rabbit spread through the Central Plateau, plague proportions were reached from the 1920s through to the 1950s (Cullen, 1995). The introduction of the Myxomatosis virus then reduced these numbers (Storey and Comfort, 2007).

The combined impacts of over grazing by domestic stock, over 100 years of burning and rabbit populations reaching plague proportions took their toll, reducing the carrying capacity of the Central Plateau by 40%; having dramatically modified the surrounding vegetation and causing the most severe sheet erosion in Tasmania (Cullen, 1995). Changing socio-economic conditions resulted in a decline in the use of high country grazing runs, which coincided with an increase in nature conservation awareness within the community. This led to the total cessation of grazing activity by 1989, when a large portion of the Central Plateau (including the study area) was incorporated into the World Heritage Area - WHA (Storey and Comfort, 2007; Cullen, 1995).

The area surrounding the study sites is now mainly used for recreational activities such as angling, camping, bushwalking, horse riding, four wheel driving (4WD) and boating, but is also used for environmental data collection and hydro electric production (Pers. ob., 2010; Storey and Comfort, 2007). A number of rehabilitation trials continue around and near Lake Augusta and are largely focused on grazing exclusion trials and rehabilitation of lunettes that have been degraded (Mundoview, 2007; Storey and Comfort, 2007; Stone, 2001; Bradbury, 1994). A 4WD track extends between the James and Ouse Rivers from Lake Augusta to Julian Tarns (some 17 km inland), but is only accessible during low levels in Lake Augusta (Pers. ob., 2010). Tracks such as theses continue to cause localised erosion (Storey and Comfort, 2007) and may also aid the spread of pathogens into the more remote parts of the Central Plateau WHA.

3.4 Geology

The Central Plateau is dominantly Jurassic dolerite which intruded as magma into the Parmeener Supergroup around 174.5 million years ago and this occurs up to a few hundred meters thick (Storey and Comfort, 2007; Cullen, 1995; Banks, 1972). The dolerite was injected between layers of the marine and non-marine sedimentary rocks that comprise the Parmeener Supergroup, deposited spanning a time period of 90-290 million years ago (Banks, 1972). Much of the sedimentary rock that was overlying the dolerite has been eroded away leaving dolerite as the dominant surface rock, accounting for about 98 percent of the Plateau area (Storey and Comfort, 2007; Banks, 1972). Underlying the Parmeener Supergroup, the basement comprises metamorphic, sedimentary and igneous rocks that predate 570 million years. These basement rocks were intruded by granite at several stages before being folded some 370 million years ago (Banks, 1972).

Around 65 million years ago, coinciding with the southern drift of Antarctica, the Plateau area rose in the north-west leaving fault controlled lowlands to the north-east, south-east and south-west (Banks, 1972). It is believed this up-faulting occurred as a major horst (up faulted block), which is tilted down to the south-east (Cullen, 1995). Dolerite cracks as it cools, leaving behind a network of joints and columns which allow the dolerite to be exploited by weathering processes (Storey and Comfort, 2007).

The other rock type present neighbouring the study area, but well within the catchment watershed, is basalt. Volcanic activity was prevalent in the study area during the Tertiary (21-37 million years ago) and sheets of basalt are visible as outcrops on the western shoreline of Lake Augusta, around Lake Ada and the Double Bar Lagoon region. However, most of the volcanic activity was present further to the south-east, west of Great Lake (Cullen, 1995; Banks, 1972). Basalt has been identified in glacial till near Julian Lakes, indicating that the basalt was present at the time of the most recent local glaciation (Cullen, 1995).

3.5 Geomorphology

3.5.1 Glacial Processes

The greatest influences through the study area, and more broadly through the western extent of the Central Plateau, have been glacial processes. During the most extensive glaciation ice extended west from Lake Augusta and covered much of the mountainous terrain of the Cradle Mountain Lake St Clair National Park (Colhoun and Hannan, 1990; Banks, 1972). At least three separate glacial climatic stages have occurred in Tasmania during which glacial advances occurred (Kiernan, 1990). The last glaciation reached its maximum some 18,000 years ago (Colhoun and Hannan, 1990). This most recent ice cover was considerably smaller than the maximum ice sheet (Storey and Comfort, 2007), which is likely to have extended some 6,000 km2 in the Central Plateau during the late Cenozoic glaciations (Kiernan, 1990). During the last glaciation ice was present in the western part of the Central Plateau, hence, the Plateau can be divided into areas of land that have been glaciated and areas that were instead subject to periglacial processes (Storey and Comfort, 2007). Contrary to the statement by Massey (2007) that the Ouse River is glacially derived, it is known that the area east of Lake Augusta remained free of ice, while to the west, glaciations are evident by ice gouged and smoothed surfaces, roches moutonnees, whaleback ridges, cirques, end and lateral moraines, hummocky moraine and erratics (Storey and Comfort, 2007; Cullen, 1995; Banks, 1972). The ice carved shallow lake basins, depressions and deposited material that has dammed or impeded the poorly organised surface drainage (Storey and Comfort, 2007; Banks, 1972).

In areas not covered by ice periglacial activity was intense, with block-streams and solifluction deposits frequently occurring and having a strong influence on surrounding soils (Cullen, 1995; Pemberton, 1986). Freeze-thaw, frost, ground ice and aeolian processes have all occurred around and to the east of Lake Augusta (Storey and Comfort, 2007). The landforms associated with these processes tend toward broad ridges with low to moderate slopes that descend to wide flat valleys where isolated large boulders are uncommon. Steeper slopes may contain boulder fields and where lakes occur they are typically clearly defined, relatively large and shallow (Storey and Comfort, 2007).

Joints and other linear structures in the dolerite have been exploited by glacial movement within the area and have given rise to the rectangular type drainage pattern which is dominantly northwest to southeast (Storey and Comfort, 2007; Cullen, 1995; Banks, 1972). There is a secondary trend in the rivers which drain nor-north east to sou-south west (Storey and Comfort, 2007; Banks, 1973). Many smaller lakes are scattered throughout the northern and north-western part of the study area and are testament to the past glaciations that occurred. Some larger lakes such as Lake Pillans have been dammed by large glacial moraines (Storey and Comfort, 2007). Numerous smaller tarns that occur in the headwater catchment of the James River are also moraine-dammed, possibly by a low ground or recessional moraine (Jerie, Household and Peters, 2003). Another example of a lake formed by glacial activity is Double Lagoon, which was formed by an ice pushed block rampart (Banks, 1972).

3.5.2 Fluvial Geomorphology

North of Lake Augusta there are two main catchments, the Ouse River to the immediate north and the James River to the northwest. A visual inspection of these catchments on 1:25,000 topographical maps immediately indicates that there might be differences in stream geomorphology. The James River is dominated by numerous small tarns that occupy shallow depressions or are trapped behind low ridges that are probably of glacial origin and are typical of multi-basinal drainage patterns as described by Brierley and Fryirs (2005, p25); although some of the more southern tributaries exhibit rectangular drainage patterns. Drainage from this catchment is torturous with a myriad of stream networks (Figure 3-1). Field reconnaissance has indicated that some of these smaller streams of the James River catchment flow underground through deep peaty material.

The upstream section of the Ouse River catchment, and also part of the catchment around Lake Augusta, both have far fewer tarns within each of their respective catchments, than does the James River valley. Rather, there are a smaller number of larger lakes with a rectangular drainage pattern, as shown in Figure 3-1 (Banks, 1972), not dendritic as described by Massey (2007). This rectangular drainage pattern is typical of landforms that have formed along right angle jointing and faulting (Brierley and Fryirs, 2005). The observations of these different stream types that occur in adjoining catchments of close proximity can readily be explained when placed in the context of parent geology and glacial history.

The maximum limits of glacial extent are known to have excluded Lake Augusta (Storey and Comfort, 2007; Cullen, 1995; Kiernan, 1990; Banks, 1972). This would have subjected the Ouse

River north of Lake Augusta to the intense periglacial activity described in Section 3.5.1and laid down the template upon which the river now lies. By contrast, west of Lake Augusta has been subject to at least three periods of glacial advance (Kiernan, 1990). Further to this, an ice divide occurred north of Lake Augusta heading west and then south-westerly (Kiernan, 1990). The location of this ice bisected the upper catchment of the James River and offers an explanation as to the moraines that block the upper catchment and the numerous small tarns formed through ice gouging, pushing, retreat and other glacially derived processes described in Section 3.5.1. In Contrast the drainage pattern of the lower section of the James River below Pillans Lake is more rectangular. It is probable that this represents the boundary between glacial and non-glacial influences. As such, the moraine damming Pillans Lake may represent a significant boundary of ice extent and thus, periglacial activity.

Drainage more broadly across the Central Plateau is represented by the Nive, Dee, Ouse and Shannon Rivers to the south, which are tributaries of the Derwent River. This is in fitting with the Plateau tilt and the legacy of glacial processes that these sou-south east draining rivers have inherited. The western, northern and north-eastern extent of the Plateau, are drained by short tributaries of the Mersey, Meander and Macquarie Rivers (Banks, 1972).

Aside from the processes influencing the dominant rivers within and surrounding the study area, Storey and Comfort (2007) briefly identified four main stream observations. These include:

- Steep streams with frequent bedrock controls;
- Broad, gently sloping, rocky valley bottoms with multiple channels;
- Low gradient rivers on deep erodible mineral sediments; and,
- Tributary streams that occur on the toe slopes of wide valleys.

The steep streams with bedrock controls are only able to erode material on a localised scale as boulder controls are frequent. These streams typically flow in multi-channels, sometimes underground, as discussed above with tributaries of the James River. Streams on rocky valley bottoms have multiple channels with insitu periglacial bedrock. These streams have significant potential for erosion, with peat often to large depths occurring between the bedrock. Their multi-channelled form typifies the disorganised nature of these streams and their ability to erode over large areas. Low gradient rivers on mineral sediments, similar to rocky valley bottoms have significant potential to erode as they have deep erodible sediments; however, these streams lack the competence to erode vertically. Rather, streams such as those to the north of Lake Augusta in the Ouse River catchment, are prone to lateral erosion, sometimes influenced by levees. The final category discussed by Storey and Comfort (2007) are the tributary stream on toe-slopes.

This type of stream is prone to both lateral and vertical incision and deposit sediment and flow diverges, likely in multiple channels, across the valley floor. This indicates the significant role that soil can play as one of the elements in the process of erosion in many of these Central Plateau streams.

3.5.3 Soils

Alpine humus soils dominate throughout much of the central plateau (Wilson, 1990). These soils have been produced since recent peri-glaciation, typically confined to areas greater than 600 m, being developed from the parent material – dolerite. The soils are typically yellow-brown consisting of a sandy clay matrix intermixed with dolerite boulders and fragments (Wilson, 1990). At the finer scale the soils within the study area consist of four main soils types. These are:

- undifferentiated sands that comprise uniforms soils;
- brown loam that comprises organic materials;
- olive to brown clay loam of gradational soils – tending yellowing brown in clay loam; and,
- brown to dark yellow brown clay loam soils with stones and gravels that comprise gradational soils (Pemberton, 1986).

The gradational soils are typically shallow with depths ranging between 5-20 cm between the horizons and a total depth of 50 cm (Storey and Comfort, 2007). These soils typically occur on the slopes and ridges and as such, tend to be well drained (Cullen, 1995). The organic soils consist of peats and bolster moorland and occur in low lying wet, cold and more western areas of the Plateau. These soils are associated with impeded drainage and are generally shallow (<30 cm) with clay – clay loam soils, interspaced rock fragments and are highly facilitative of solifluction (Storey and Comfort, 2007; Kiernan, 1990; Pemberton, 1986). The other main soil type of the Plateau is that of the uniform sands that are the deepest soils within the area, typically greater than 1.5 m deep. These latter soils have been the topic of much discussion as they comprise the source material for many of the lunettes (sand ridges) that boarder the eastern and south-eastern flanks of lakes; of which the Lake Augusta lunettes are the largest example (Mundoview, 2007; Storey and Comfort, 2007; Stone, 2001; Cullen, 1995; Bradbury, 1994; Pharo and Kirkpatrick, 1994; Pemberton, 1986; Banks, 1972).

3.6 Hydrology

Aside from the geological history, landscapes continue to evolve geomorphologically through predominantly fluvial processes, with water being the key element, particularly on the Central Plateau. All of the above mentioned soil profiles are impacted by the harsh freeze-thaw pattern of the Plateau, in particular the process of needle ice formation, also referred to as frost heave (Storey and Comfort, 2007). The ice forms beneath the soil surface from frozen water lifting the crust and material frozen to it as the soil surface freezes. Needle ice is capable of lifting a 5 kg rock 1 cm off the ground surface (Storey and Comfort, 2007). While this may not sound significant, this can have severe implications for rehabilitation efforts, such as sites around the Lake Augusta lunettes.

Although a fine scale impact, processes of frost heave can impact areas on a catchment scale due, especially given the altitude of the Plateau and the extent of bare ground. However, rivers too exert a catchment influence, particularly relative to their drainage patterns and headwater storage capacity. Lakes or peat land in particular, can act as sponges soaking up flows, storing the water for slower and longer discharging periods (Jerie et al. 2003). This will have an impact on the erosive potential and bedload carrying capacity of a given river. Gordon et al., (2004) identify catchment area as one of the more important basin descriptors as it influences the number and size of each stream along with the potential water yield. In order to expand on the catchment hydrology relative to the study area, a watershed model was created for three sites that define the sub-catchment area (the whole study site occurs within the upper Ouse Catchment) for the current study (Figure 3-5). These are the James River catchment, the Ouse River reference catchment and the Ouse River study catchment. The watershed delineation in Table 3-1 shows the sub-catchment area and water body extent. The sub-catchments indicate that they represent good paired study catchments due to their similarities in catchment size (Table 3-1).

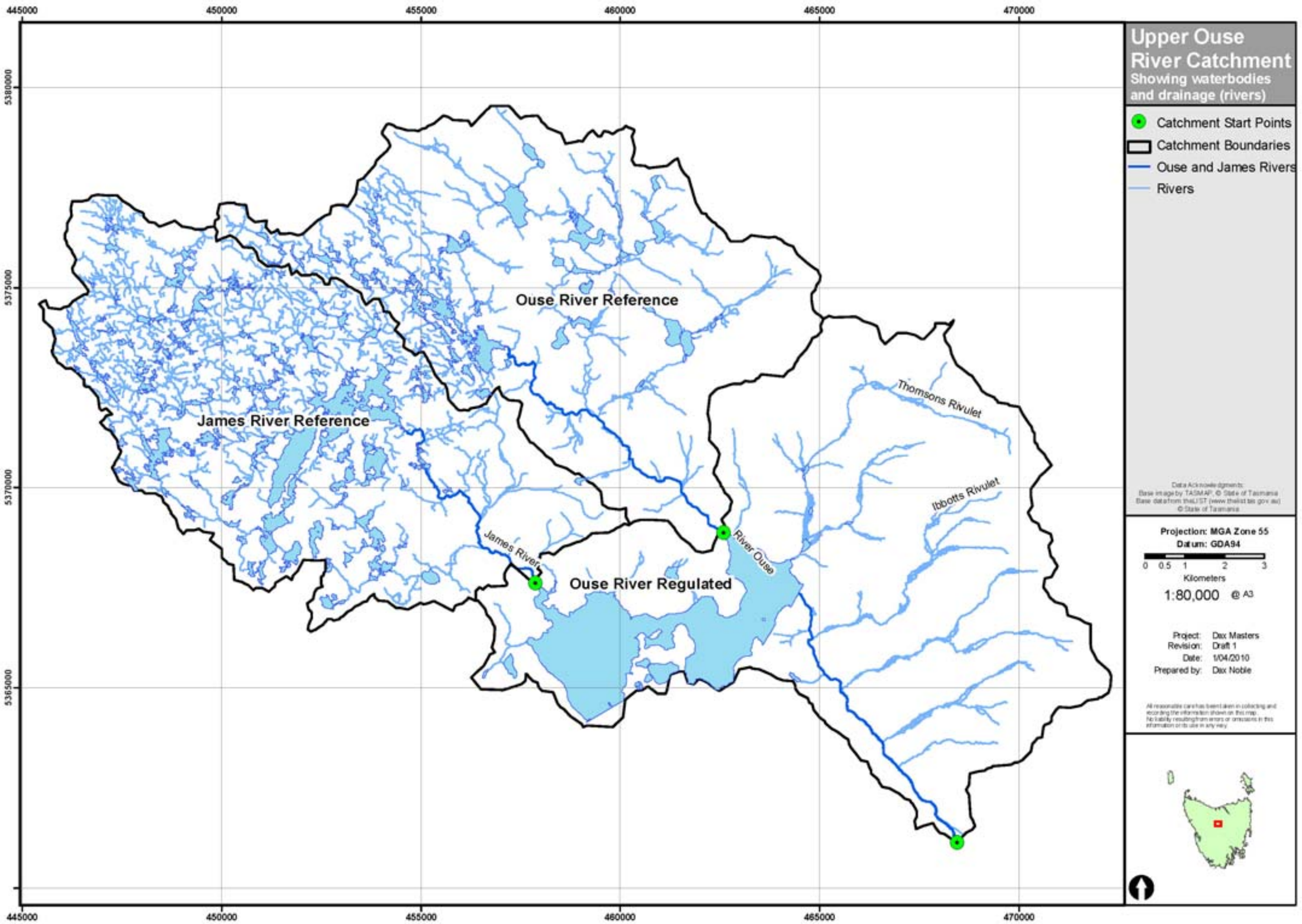


Figure 3-5 Water-body extent and drainage network for each of the sub-catchments

Table 3-1 Sub-catchment and water body size within the study area

Sub-catchment	Catchment area (km^2)	Water body Area (km^2)
James River	81.518	8.688
Ouse River Reference	79.649	4.408
Ouse River Regulated	104.488	12.351

As can be seen from Table 3-1 there are some similarities between the sub-catchments. The James River sub-catchment at 81.5 km^2 is almost exactly the same size as the Ouse River reference sub-catchment size of 79.75 km^2. The Ouse River regulated sub-catchment is slightly larger with nearly 105 km2 of surface drainage. Interestingly, the water body area of the two reference sub-catchments added together is almost the same as the study sub-catchment area, largely due to Lake Augusta. It is also note-worthy to highlight the water body difference in Table 3-1 between the reference sites with the James River catchment having almost double the storage capacity in tarns and larger water bodies to that of the Ouse reference sub-catchment. This aspect further strengthens the evidence of the glacial limits that extended over the James River catchment but failed to reach the lower parts of the Ouse River catchment.

Flows downstream of Lake Augusta are controlled by Augusta Dam. The dam was constructed between January 1951 and May 1953, the latter including the period of initial filling. The dam is a 13 m rock lined dam with a sloping clay core and a concrete gravity wall crest that discharges water downstream via twin 1.52 m square reinforced concrete conduits. Water is controlled by upstream still-water valves and control valves on the downstream side (Hydro Tasmania, 2005b). The full supply level (FSL) of the reservoir is 150.62 m ASL and the nominal minimum operating level (NMOL) is at 1141.63 m ASL. The storage operating rules recommend the lake be maintained at no less than 1146.63 m ASL (Hydro Tasmania, 2005c). Lake Augusta holds 35 discharge days of water, meaning that with no inflows, water can continuously be discharged for downstream uses for 35 days (Greg Carson, pers. comm.., 2010). The crest of the dam is at 1152.98 m ASL, however a separate concrete gravity wall spillway exists 500 m-1 km further to the west. The spillway crest level is FSL (1150.62 m ASL) and beyond this level flows spill, flowing downstream over the access road and overland down to the Ouse River – regulated reaches (Hydro Tasmania, 2005b). There is no defined channel natural or otherwise, the water flowing over the spillway simply takes the most direct route down to the Ouse River. The upper section of the spillway has a semi-defined channel, while closer to the Ouse River it is difficult to distinguish where flows enter as the water appears to spread and have several flow paths joining the Ouse River.

The Ouse River below Augusta Dam forms part of a myriad of diversion channels, canals, catchment transfers and inter-basin transfers (Figure 3-6). Water is primarily used for the generation of hydro-electricity; however, water is also allocated for other uses each year including irrigation (9,718 ML), stock and domestic (64 ML), water supply (69 ML) and other uses (107 ML) within the catchment (DPIW, 2006). The primary off-take in both distance and water volume is Liawenee Canal, situated ~9 km downstream of Augusta Dam. The canal transfers water between Lake Augusta and Great Lake, primarily for hydro-electricity generation. There is no consideration given in the Storage Operating Rules (Hydro Tasmania, 2005c) as to how water is transferred between these storages (e.g. discharge volume per day or flow velocities), the river is essentially utilised as a conduit for water based on lake level (Mundoview, 2007).

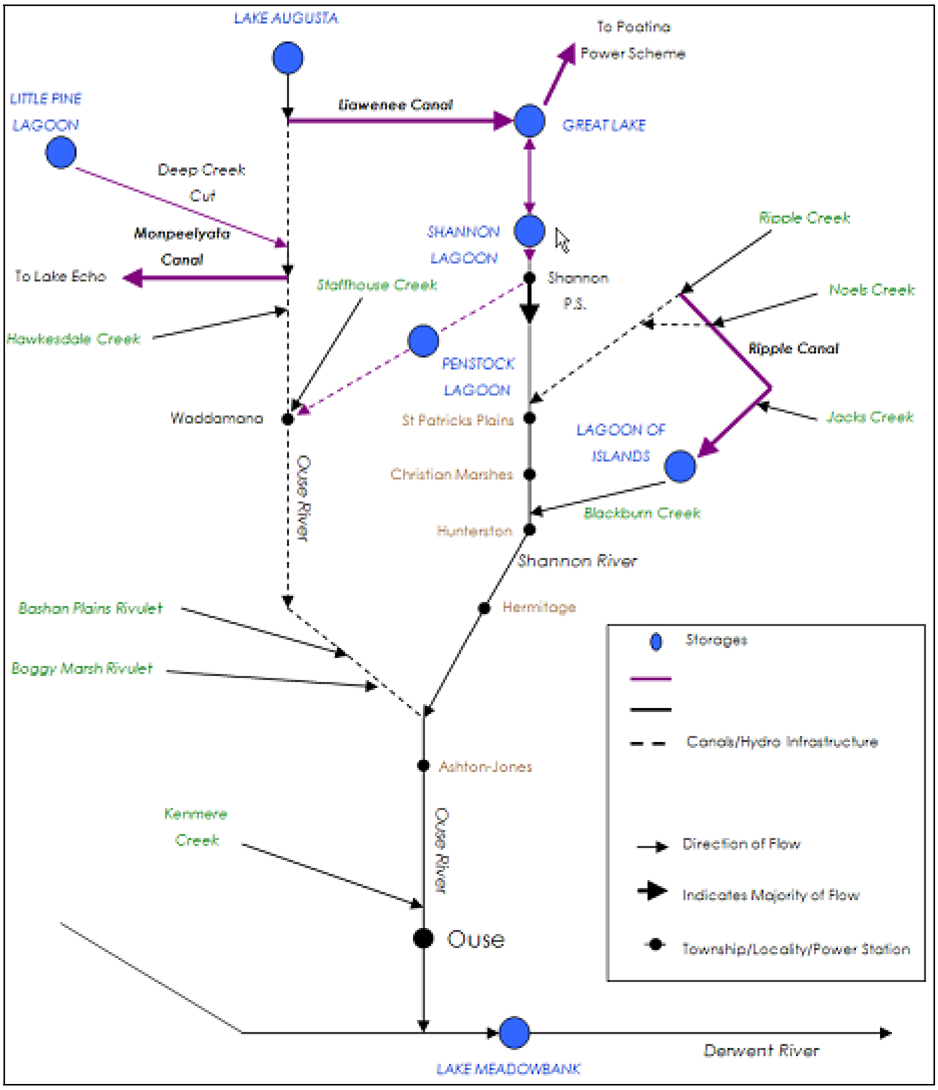


Figure 3-6 Ouse River and Neighbouring Catchments showing the network of Water Transfers and Storages (Cox and Graham, (2006)

3.7 Riparian and Catchment Vegetation

3.7.1 Vegetation Structure and Extent

The vegetation of the central plateau is diverse, covering areas of forest, woodland, shrubland, heathland grassland, sedgeland and herbfields (Storey and Comfort, 2007). The study area comprises broad gullies and slopes that encompass much of these vegetation types. As the altitude of the area is nearing the upper margins of the tree line small site specific variations can often mean large vegetation alterations. Apart from altitude, additional controls on vegetation growth within the area include parent soil, slope aspect, drainage, fire history, near freezing and freezing temperatures and storm events (Storey and Comfort, 2007). Strong predominantly westerly prevailing winds and animal browsing should also be included as an additional control on vegetative growth and recolonisation (Phillip Barker and Anita Wild, pers. comm., 2009) as browsing, which often disturbs the surface matting, combined with prevailing winds, often leads to a micro-scale blowout, more commonly seen in destabilised sand dunes (Storey and Comfort, 2007; Bradbury, 1994).

There are distinctive grasslands in areas of deeper soil development near Lake Augusta, while the barer rock-fragment covered ground with shallow soils contains occurrences of fjaeldmark. Elsewhere wet alpine heaths and bogs occur in sites containing poor drainage that support bolster moorland. *Eucalyptus coccifera* are dominant on the tree-line often in stunted form, while on the flats native *Poa* spp. grassland can dominate. Other species found across the plateau in the Lake Augusta region include *Abrotanella forsteroides*, *Pterygopappus lawrencii*, *Astelia alpina*, *Gleichenia alpina*, *Empodisma minus*, *Restio australis, Lepidosperma filiforme* and *Richea acerosa* (Pemberton, 1986). Where repeated fire has occurred *Helichrysum hookeri* and *Olearia algida* have invaded the former grasslands. On the ridges *Orites spp.* may dominate, while *Grevillea australis* has been shown to be useful for revegetating areas suffering sheet erosion (Pemberton, 1986).

Throughout many of the riparian margins in the Plateau, Pencil Pine (*Athrotaxis cupressoides*) 'groves', comprising small groups of trees grow with trunks in the stream or within the wetted perimeter (margin of intermittently damp soil at the toe of a river bank). Such groves occupy distinct pockets in sheltered valleys of the James River. Other species specific to the James River catchment include *Carpha alpina* in the grasslands and *Richea acerosa* in bogs. Woody species include *Lissanthe montana* and *Monotoca glauca*; although, similar to the Ouse River catchment, *O. algida* and *H. hookeri* have invaded fire disturbed areas (Pemberton 1986). One final point worthy of mention is that the vegetation across the entire catchment is quite diverse and with the distribution of species being controlled by temperature soil, aspect, drainage and fire history, small variations in site conditions can have major influences on vegetative composition (Storey and Comfort, 2007; Cullen, 1995; Pemberton, 1986).

3.7.2 The Impacts of Fire on Vegetation

As alluded to above, fire history plays an important role in controlling vegetation growth and extent. Fire can also have a significant impact on the removal of vegetation from an area, which in turn influences the sensitivity of some Plateau areas to erosion. While it is clear the Aboriginal inhabitants of the Plateau area used fire for clearing access routes, most accounts of Aboriginal habitation relate to the lower eastern (Storey and Comfort, 2007) or southern areas of the Plateau (Pemberton, 1986). Rather it is the 150-170 years of fire and grazing since European settlement that has exerted the greatest impacts and change on vegetation across the Plateau (Cullen, 1995) and the most widespread and severe sheet erosion in Tasmania (Pemberton, 1986).

Several small fires are known to have burnt 1,500 ha to the west of the study area in the 1930's; however, the largest wild fire on record occurred over a 6 month period from 1960-61, burning over 310 km of land spreading from Travellers Rest Lake to Lake Mackenzie (Storey and Comfort, 2007; Pemberton, 1986). Other smaller fires have occurred since on the Plateau (Storey and Comfort); however these have been more localised and less devastating than those of the 1960's. In some areas, soil pedestals are present that appear to be vegetated islands in areas of otherwise bare earth. These indicate that the fire caused a loss of up to 30 cm of the soil profile. This soil loss has been caused through the initial fire destroying the peat, after which wind, grazing or water erosion (or a combination of all three) have removed the upper soil layers to expose a mineral underlay. This mineral layer is then subjected to erosive processes that may lead to further soil loss (Pemberton, 1986). Pemberton (1986) writes "*After more than twenty years there has been extremely limited recovery of both soil and vegetation. Natural recovery…takes many decades, if it occurs at all*". A recent review (Storey and Comfort, 2007) has highlighted that after nearly 50 years since the most significant fires the situation has not significantly improved with many areas remaining devoid of any vegetation. If nothing else, this highlights the significant impact fire can have on these alpine environments, especially when coupled with intensive grazing practices.

Chapter 4 Methods

4.1 Introduction

The current study was devised to record the composition of fine sediment in the Ouse River downstream of the Augusta Dam and if there is any potential to increase the availability and stability of this fine sediment, if as predicted, fine sediment is being flushed downstream to the Liawenee off-take. Brierley and Fryirs (2005) state that it is the inorganic sediment (silt, sand, gravel, and cobble) that primary determines the abundance and diversity of many aquatic organisms, including macroinvertebrates, macrophytes, and algae. It is posed therefore that the ecological health will improve and facilitate natural ecological succession in regulated reaches of the Ouse River, if flow regimes can be modified to limit their scouring and transportation that bay be occurring and caused by water transfers. However, before any flow modification is considered, the presence or absence of the fine sediment fraction needs to be quantified initially. As a comparative analysis to set a benchmark, the Ouse and James Rivers upstream of Lake Augusta were identified as reference sites.

Current release rules are solely intended to facilitate water transfers between Augusta and Great Lake to maximise the production of hydro electric power. No consideration is given to the impacts of these releases on stream health or how the water is released. Massey, (2007) identifies the area downstream of Lake Augusta as being a hostile environment that is comprised of large instream boulders that provide some diversity in the largely glide to rapid flow that is instigated during transfer events between Lake Augusta and Great Lake (via Liawenee Canal). Massey (2007) suggests that sediment being trapped by Augusta Dam is in part replaced by input from adjoining tributaries; however, due to sudden high flow releases from Augusta Dam, this sediment becomes entrained and effectively flushed from the system limiting ecological succession.

In order to quantify these stated "limits to ecological succession" caused by the operation of Augusta Dam it was decided to devise a study to quantify the presence of fine sediment downstream of Augusta Dam. Fine sediment was determined to be sediment with a b-axis diameter of less than 64 mm, which using the Wentworth scale (Gordon et al., 2004) is in the very coarse gravel group. As river sediment can exhibit a large degree of site variability it was decided to utilise the catchment inflows upstream of Augusta Dam as control (reference) reaches. Section 3.6 has already identified the suitability of using the two main inflows, James and Ouse Rivers, as references for natural stream condition.

Several methods for field measurements of river sediment were considered. Originally, scour chain employment was planned; however, time limitations for gathering field data, acquiring approvals to undertake work in the TWWHA, and issues in relation to the suitability of field sites for this use, prompted a re-think of field techniques. It was therefore decided to trial a relatively new technique for rapidly gathering sedimentological field data, via a program called Sedimetrics® (www.sedimetrics.com). This component of the study focuses on the composition of the bed material utilising the Sedimetrics® software. Bedload transport is then derived through the use of empirical equations in the BAGS software (Section 2.5.5) to extrapolate sediment transport rates in all sub-catchments. Since bedload transport can be problematic to accurately calculate, especially given the considerations in Section 2.5.3, sediment transport rates are provided an indication of likely bedload transport rates.

Bedload movement in streams requires discharge and slope. None of the rivers upstream of Lake Augusta are gauged, therefore field reconnaissance was required to complete point-in-time gaugings of field sites. Cross-sections of the upstream sites were completed either prior too or during the stream gauging field trips to gain a better understanding of the physical form of the stream bank profile. Other relevant data collected from field sites included stream width, bed and bank shape and surrounding valley planform. This data was recorded on modified 'AUSRIVAS Physical Assessment Protocol Field Data Sheets' (Parsons, Thoms and Norris, 2002.

4.2 Fluvial Geomorphology

This section describes both the qualitative and quantitative data collection methods employed for field investigations. The qualitative methods include compilation of landform, bank-channel shape, bank angle, presence of any bars or islands, fish passage, channel modifications, sediment shape and instream flow types from observations at each field site recorded on physical form data sheets. Quantitative data measurements included set area photographs within distinct sediment boundaries for later processing with the Sedimetrics® software, Digital Gravelometer™. Field and office based data was collected in the field or processed using the Arc GIS 9.2 platform and used as an input for the calculation of sediment discharge in the BAGS software.

4.2.1 Site Selection

In order to determine the sediment composition of the regulated sub-catchment eight sites were preliminarily selected for field investigation from topographic maps. To ensure an even comparison between study and reference sites, eight sites were also chosen using topographic maps in the James River sub-catchment and also the Ouse River sub-catchment. Appendix A shows the name given to each study site and the map grid references (easting and northing). Regulated and reference sites were selected on riffles or gravel bars upstream and downstream of tributaries in a similar approach to that of Sear (1996). This was done to provide an even spread of sites and ensure that data collection was not biased toward sites that may receive sediment from tributaries. The intent of these locations is to gain an understanding of the overall sediment composition at each of the study sites in an unbiased approach and to assess then any sediment variability between each of the three main study areas, termed sub-catchments. Project time constraints limited the collection of sediment data within tributaries.

Site Access

Site access is by foot, the closest site is OS1, being located a few hundred metres downstream of Augusta Dam and is accessible from the gauging station. The furthest site, J8, required a 6 km walk around the western side of Lake Augusta and up the James River valley. Field reconnaissance trips were completed for the Ouse River reference sites first on 08-03-2008 to micro-locate each field site and determine its suitability (Figure 4-1). The James River reference sites (Figure 4-1) were visited 30-08-2008 and the Ouse River study sites Figure 4-2 were visited 06-09-2008, also to determine site suitability.

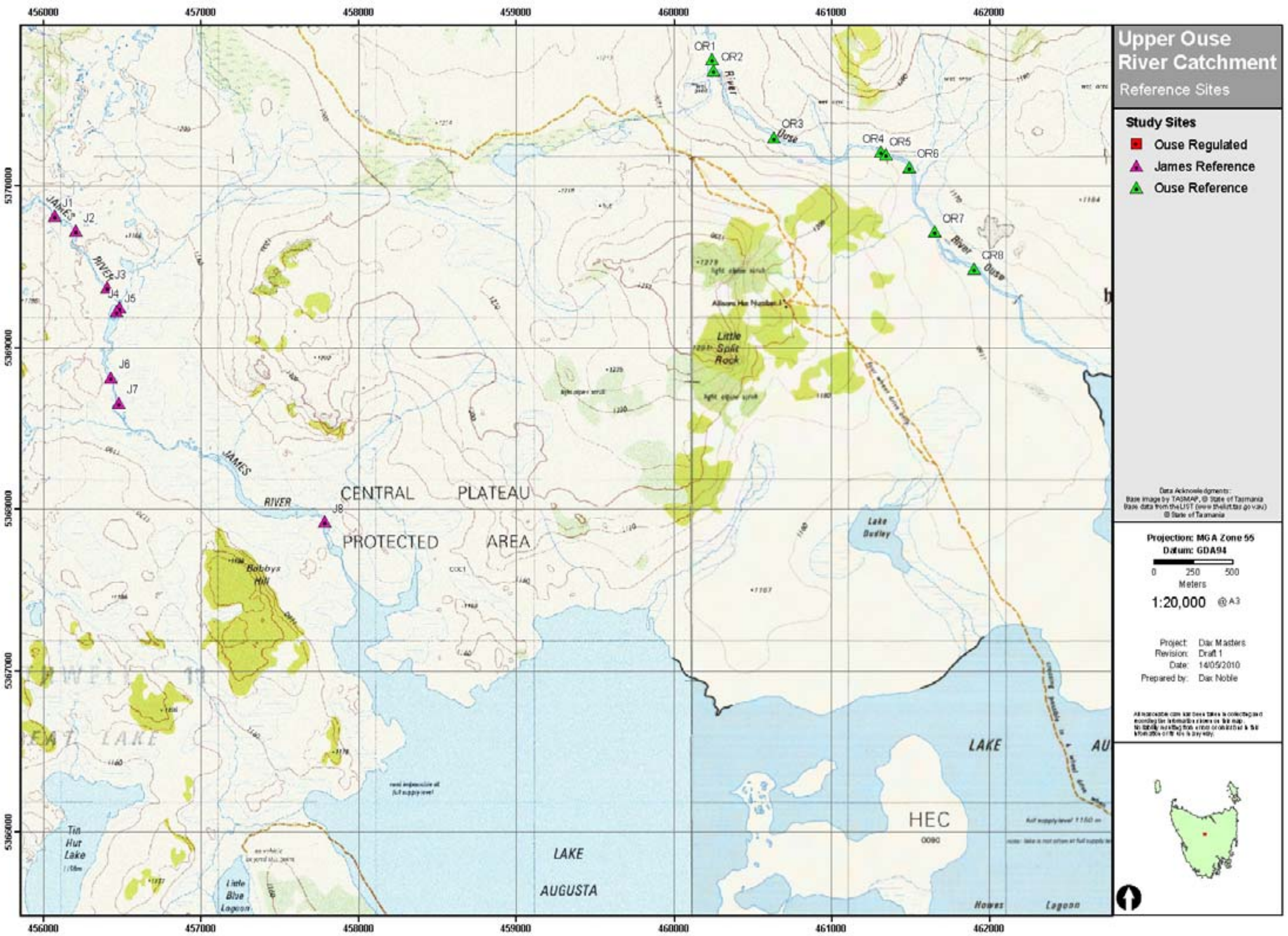


Figure 4-1 Final location of reference sites

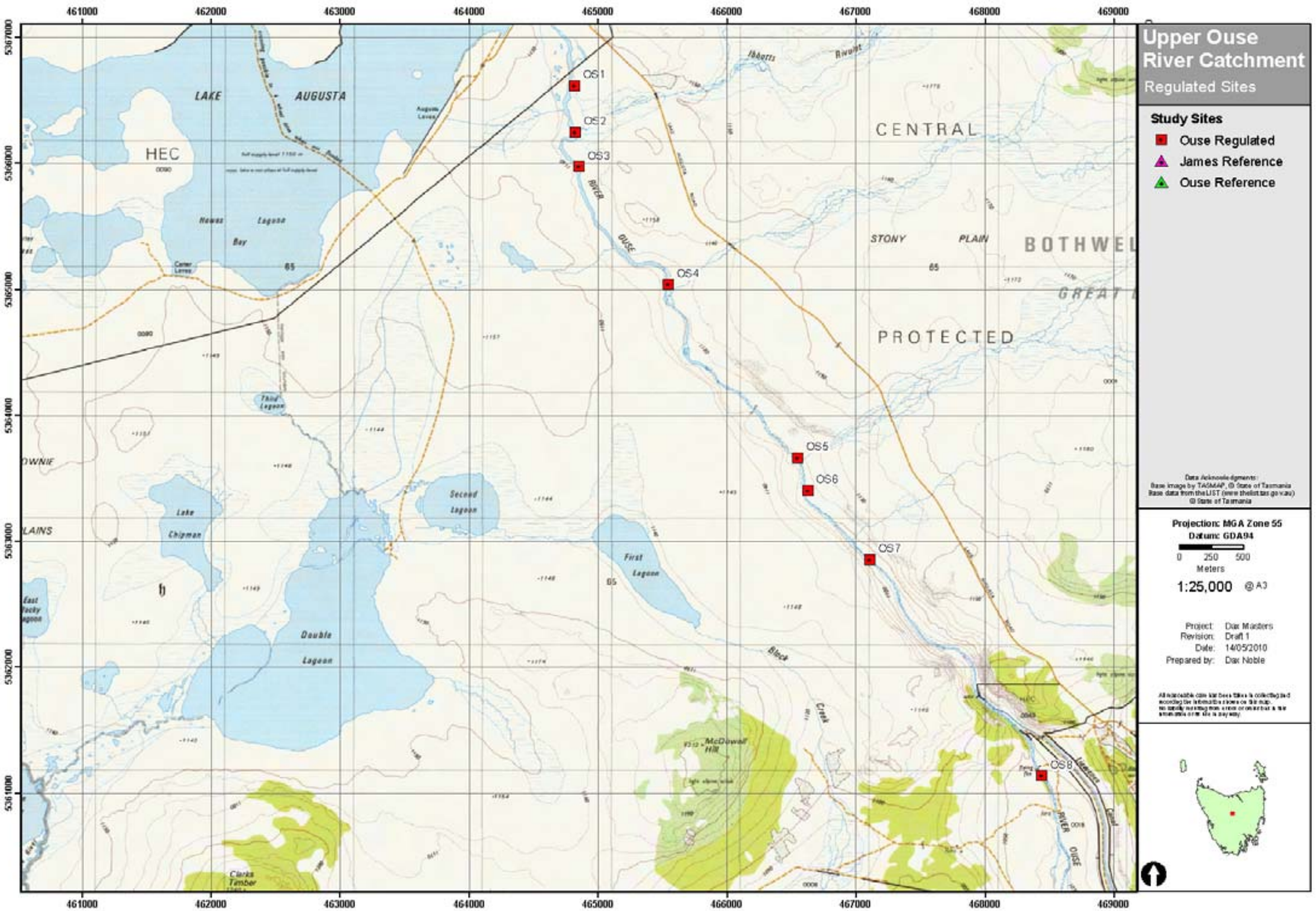


Figure 4-2 Final location of regulated sites

4.2.2 Site Analysis

All sites were sketched on data sheets during final analysis (Sedimetrics®) field visits and the location of each photo sampling point was recorded. Site photographs were taken using a Canon IXUS 80, 8MP camera or a Canon 450D SLR 12.1MP camera. A Leica range-finder was used to determine reach lengths and bank widths and a hand-held Garmin eTrex GPS was used to record field sites. The naming of sites is consistent for all sub-catchments with site 1 being the most upstream site and site 8, the most downstream.

Physical form data sheets were completed during the final site visits to ensure that information on field sheets was representative of the final sampling location. After an initial search for data sheets it was decided to use the "*AusRivAS Physical Assessment Protocol Field Data Sheets*" (Parsons, Thoms and Norris, 2002) as valley, channel and bank information required by these data sheets complemented the substrate information collected for the sedimetrics® software. Field sheets were modified to remove superfluous ecological data and only capture physical form data. The results of the site analysis are presented in Section 5.1.1.

4.2.3 Hydrology and Cross Sections

The current meter method for determining discharge (Q) discussed in Section 2.3, and shown in Figure 2-1 was used for measuring flow velocity at each site. Standard Hydro Tasmania 'Discharge Measurement' field sheets were used to record distance from bank, depth, depth of observation, current metre contacts and length of time for each record. In the Hydro Tasmania Consulting office, flow data were then entered into the Hydro Tasmania *Timestudio* database, which calculates discharge (cumecs), area (square metres), mean velocity (metres per second) and wetted perimeter (metres).

To measure the cross sectional profile of the stream at each gauging site a dumpy level was used in conjunction with a survey staff. Recordings of break-in-slope including, stream thalweg, edge of bank, top of bank and water-level were made on Hydro Tasmania 'Loose Level Sheet' for survey profiles. The stream gauging and cross sections were completed over two weekends requiring four days of field work; trip date, sites and purpose are shown in Table 4-1.

Table 4-1 Gauging and cross section field trips

Date	Sites	Trip Purpose
21-2-2009	J8	Cross section
22-2-2009	J1 & OR1	Cross section
13-3-2010	J1 & J8	Gauging
14-3-2010	OR1 & OR8	Gauging
14-3-2010	OR8	Cross section

The stream gauging of both rivers was completed in one weekend, as were the river cross sections. However, the gauging field work was considered to be more important to complete in one weekend so that flow comparisons between the catchments were not influenced by different rain events. Weather during completion of cross sections and gaugings was dry and warm. The sites shown in Table 4-1 represent the most upstream and downstream of the reference sites. This approach was purposefully taken so that flow entering and exiting the reference area was known. Flow data for the upstream (OS1) and downstream (OS8) Ouse regulated sites was exported from the Hydro Tasmania *Timestudio* database by Senior Technical Officer Lukas Salkeld, as point-in-time data for the 14^{th} March 2010 at 2pm to coincide with the field gauge results. The gauging/stream width information collected from these sites also forms part of the inputs required for the BAGS software. The results of the stream hydrology data obtained from the *Timestudio* database are presented in Section 5.1 Hydrology and Cross Sections. In addition to spot data, long-term flow data averages were also exported from the Timestudio database and area also presented in Section 5.1 Hydrology and Cross Sections.

4.2.4 Photographic and Statistical Analysis

Collection of Field Data

The photographic data collection is an important component of the field work, because it forms the basis for comparing sediment characterisation between sub-catchments and data input for the sediment transport model (BAGS). The basic principle of this method has been discussed in Section 2.5 Photographic Analysis. The collection of field data for this specific study involved the following equipment:

- Canon 450D SLR 12.1MP Camera (with a Canon 17-85 USM EF-S Lens and Canon external mount flash unit 580EXII);
- Plastic quadrat frame measuring 1 mx1 m, collapsible for easy transport;

- Plastic zip-ties to secure around the quadrat as internal markers

Site photographs were completed over 6 days and 5 separate trips. The date and details of each trip are shown in Table 4-2. As can be seen from Table 4-2, trips were not all completed in the same year, however an attempt was made to capture the data for each sub-catchment in the same field trip, although this was not possible for the Ouse River reference site. The James River reference sites were completed in summer 2008, the Ouse River reference sites in summer 2008-2009 and Ouse River study sites were completed summer 2010 (Table 4-2). As previously stated the difficult access into each site meant that access was only by foot and on several occasions required an overnight stay, either camping in a tent or utilising the local National Parks and Wildlife Service huts.

Table 4-2 Dates and location of when field data were collected

<table>
<tr><th>Date</th><th>Sites</th><th>Notes</th></tr>
<tr><td>21-2-2008 –</td><td>J1-J6</td><td rowspan="2">Walked up James River camping beside sites J4-J5, completed OS3 and walked back to Augusta West</td></tr>
<tr><td>22-2-2008</td><td>J7-J8 & OR1-OR3</td></tr>
<tr><td>07-3-2009</td><td>OS-8</td><td>Didn’t use, images recollected</td></tr>
<tr><td>12-4-2009</td><td>OR3-OR8</td><td>Finish all Ouse River reference sites</td></tr>
<tr><td>13-2-2010</td><td>OS1-OS4</td><td>Usable photos collected</td></tr>
<tr><td>20-2-2010</td><td>OS5-OS8</td><td>Usable photos collected</td></tr>
</table>

As the upper Ouse River is an ungauged catchment in this location, being in the TWWHA, the hydrology in the winter of 2008 was not known and a degree of bedload movement may have occurred between sampling periods. Table 4-2 shows that there was a year between sampling OR 1-3 and OR3-8, during which time some bedload movement is likely to have occurred. However the distance between sites 3 and 4 is sufficient that it is unlikely any significant sediment transport occurred that would impact upon the results of this study. The timing between photographic periods is therefore not considered to be a significant issue.

The collection of digital photographs for analysis in Digital Gravelometer™ was limited to areas of dry grains (wet interstitial spaces are ok according to Graham et al., 2005b). However, both the Ouse (regulated and reference) and James Rivers have a distinct lack of ‘cobble’ bars. Therefore sampling was limited to sections of the streambed that were exposed during lower flows. The sampled areas essentially behaved as cobble bars during periods of low flow.

Once on site, pockets of available (dry) sediment exposed within the each river were observed and a qualitative assessment made on the variability present at each site, as per methods described by Kondolf (1997) for site identification prior to completing a pebble count. The quadrat was laid over visually distinct populations of sediment so that sampling could occur within each distinct population (Kondolf, 1997). Methods described by Graham et al. (2005b) were followed, which involved:

- shading the photograph with a sheet when in direct sunlight;
- holding the camera vertical and turning the flash to 'always on'; and
- photographing the sediment and ensuring the tags were in each photo and no frame present.

At the time of sampling it was believed that no frame in the photograph meant that the control points (tags protruding into the photo) were selected and this clipped out any frame in the entire photo and left the 'sample area' present. However, frame was included and processed as sediment in some of the photos, which did result in some photos being rated lower.

Processing Images

The Sedimetrics® software was downloaded and trialled over a 21 day period and appeared to produce mixed results. The software developers were contacted who advised that some of the processing parameters may need adjusting to correct image processing errors (Graham, 2009, pers. comm.). A Digital Gravelometer™ education software licence was purchased and has been activated for use with this thesis.

Once installed Digital Gravelometer was installed, site images were loaded into the program and sorted by sub-catchment. The original photo number was used for each site as a suffix. As an example the James River reference reach photos were 0537 and 0538, these were renamed to 0537_J1 and 0538_J1 indicating that two photos represent the sediment distribution at site J1. A new project was set up in the Digital Gravelometer™ software and a total of 53 photos were analysed. A spreadsheet was set up to record the site, image name, notes on any adjustments made and the final quality of the processed result was given a rating of 1 (extremely poor) to 10 (perfect), the visual rating based assessment scale is shown in Table 4-3. If an image received less than a 5/10 it was decided not to use that image because the result of the digitising was too poor. The spreadsheet showing the individual images used and those excluded from further analysis is shown in Appendix B. A total of 53 images were processed, with seven of those images processed produced un-useable results, leaving 46 useable images for processing (Table 4-3).

Table 4-3 Visual rating table used for determining the success of the Digital Gravelometer™ output.

Rating	Interpretation of Result	Number in Category	Data Use
1	Extremely poor	1	7 Image results too poor – do not use
2	Extremely poor	2	
3	Very poor	1	
4	Poor	3	
5	Fair	13	46 Images considered satisfactory to excellent for use
6	Fair-good	6	
7	Good	10	
8	Very good	11	
9	Excellent	6	
10	Perfect	0	

A complete manual for processing each image has been developed (Loughborough University Enterprises Limited, 2006) and as such only a summary of the process is listed below, for further details the website www.sedimetrics.com should be viewed.

The procedure for processing each image involves:

- Loading the image and identifying the control points;
- Selecting any output or processing options;
- Measuring individual or aggregated samples;
- Generating the grainsize report; and
- Exporting the raw data (if desired).

Image data from each stage of the processing stage were exported along with the report. The image results were amalgamated at each individual site (where processing with Digital Gravelometer™ produced useable results). The processing stages of the image software are shown in Figure 4-3, which shows that there are three main stages in image processing. This involves pre-processing, image processing – analysis stage and the final derivation of a grain-size distribution plot. Examples of the grain size distribution exports are presented in Section 5.1.3.

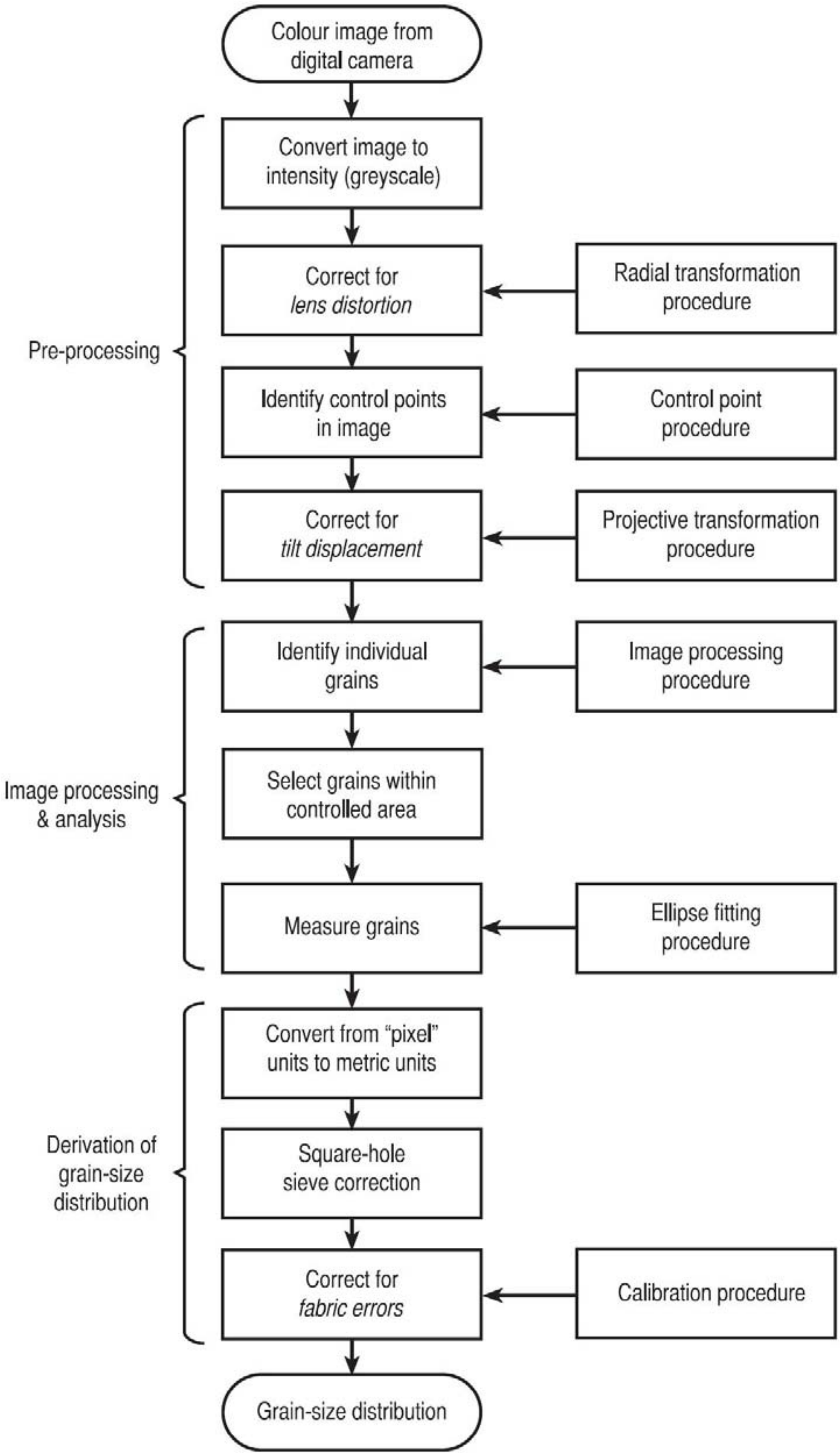


Figure 4-3 Image processing stages in the Digital Gravelometer™ software

Post Processing of Raw Data

The raw data was exported for each of the individual images that had a score of 5 of greater for visual performance. Data were sorted and organised using Microsoft Excel into sediment size classes after Bovee (1982, in Gordon et al., 2004). To sort the sediment into classes the data analysis tool-pack was loaded into Microsoft Excel and data analysis used to construct histograms of each 'bin'. One minor modification was made to the size classes (bins) to ensure no duplication of data. This involved increasing the start point of the next consecutive category by one. As can be seen by Figure 4-4, if a particle with a b-axis of 50 mm is selected, it is unclear as to whether the particle falls into category 3 or 4 without this modification.

Substrate description
Fines (sand and smaller)
Small gravel (4–25 mm)
Medium gravel (25–50 mm)
Large gravel (50–75 mm)
Small cobble (75–150 mm)
Medium cobble (150–225 m
Large cobble (225–300 mm)
Small boulder (300–600 mm
Large boulder (>600 mm)

Sediment Size Classes
Fines 0-3
Small Gravel 4-25
Medium Gravel 26-50
Large Gravel 51-75
Small Cobble 75-150
Medium Cobble 151-225
Large Cobble 226-300
Small Boulder 301-600
Large Boulder >601

Figure 4-4 Particle size class after Bovee (1982, in Gordon et al., 2004) left, and the modified Bovee size classes, right.

To rectify the issue of overlapping sediment size classes after Bovee (1982) were modified. The modified classes are shown in Figure 4-4 that ensure there are no overlapping sediment classes. The Australian Standard® AS 1289.3.6.1-2009 (Standards Australia, 2009) particle size limit classes were not used as there was a dominance in sand silt and clay for 50% of the classes, which would ultimately bias the results given that most data has been truncated at approximately 8 mm. Similarly the Wentworth classification method was focused on finer sediment, with the largest boulder being over 250 mm. The catchment is largely comprised of cobble-boulder based streams; therefore the modified sediment size classes of Bovee (1982, in Gordon et al., 2004) were adopted as shown in Figure 4-4.

Statistical Analysis

Once the data was sorted into sediment classes as count data they were then imported into the statistics package SPSS for analysis. The dataset was set up with a 1 or 2 coding, which SPSS can use to either include all or part of a dataset based on the coding. The data were analysed two ways: initially by selecting out only the highest rating photos (Table 4-3); and secondly, by including the complete dataset, that is all photos with a rating of 5 or greater (those with a score lower than 5 were permanently excluded as they may have introduced significant error and are not discussed any further). The selected and the complete data were then analysed separately.

To gain an overview of these data, tests for differences in individual sediment size classes (Figure 4-4) were completed by comparing means +/- 2 SE using SPSS. These data were then tested for homogeneity of variance to ensure it did not violate the assumptions of ANOVA. A one way ANOVA test was then completed on the selected dataset to determine if there were any statistically relevant differences between the three sites. The ANOVA test only identifies whether a significant difference does or does not occur, ANOVA does not identify where any difference occurs (Dytham, 2003). To determine which groups of data are statistically different a *post-hoc* test is required. SPSS has several options for pos hoc testing and two different tests were selected. These are the least significant difference (LSD) test and the Tukey HSD (honestly significantly different) test. Both tests were completed to determine the suitability of the data to one test over the other.

To further investigate the differences within the data an ordination plot was produced. To complete this, data were square root transformed to reduce the impacts of high count values on similarity indices. The Bray-Curtis dissimilarity co-efficient was calculated for the different photo-transects within the sites. Non-metric multidimensional scaling (MDS) using count data for sediment classes was undertaken to produce ordinations. Analyses were undertaken in Primer 6.1.7 using default settings (25 restarts with minimum stress of 0.01). The optimum number of dimensions was selected after assessing the stress values. Solutions with stress values of greater than 0.2 would have been rejected in the present study due to increasing likelihood of misleading interpretations (Clarke, 1993).

Ordination is an exploratory tool that is used to order the sediment class groups in space, relative to other groups, dependant on the similarity of sediment composition evident between regulated and reference sites. The similarities between the quadrats (in this case photographic quadrats) are calculated and plotted in space as a point in a coordinate system and represented in a scatter diagram (Hydro Tasmania, 2005d). Ordination diagrams display similarities between sites and similar sites tend to cluster, while greater spread indicates a difference in the sediment class composition of the sites (Hydro Tasmania, 2005d). Through the utilisation of ordination, data can therefore be explored to assess if expected groupings are occurring, such as differences between sediment compositions at regulated and reference sites.

The SIMPER program, within PRIMER, was then used to determine which (if any) sediment classes were contributing most to the degree of similarity and dissimilarity within and between sediment classes on the basis of that abundance.

4.2.5 Sediment Transport (BAGS)

The derivation of bedload transport involves a combination of three parameters, the surface layer (sometimes referred to as the armour layer), the substrate that is typically comprised of fine gravel (< 2mm) and the bedload, which moves in contact with the bed (Pitlick et al., 2009). The difference in surface to subsurface particle size is shown visually in Figure 4-5 and graphically in Figure 4-6. The BAGS software identified in Section 2.5.5, has been utilised to calculate bedload movement (given as kilograms/metre/second) at the upstream and downstream extent of both of the reference sites and the study site (J1, J8, OR1, OR8, OS1, OS8). These sites were selected because they coincide with sites where stream gauging and cross-section measurements have been completed.

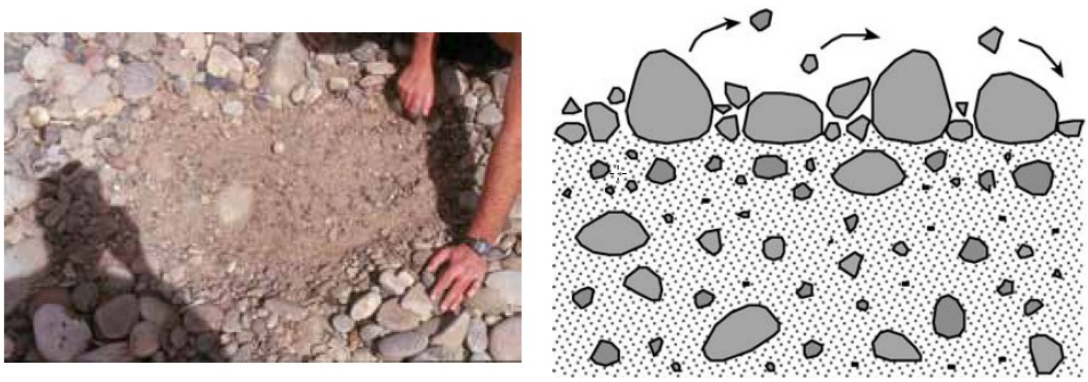


Figure 4-5 Comparison between the armoured surface layer and the substrates in a typical gravel-bed stream (Pitlick et al., 2009).

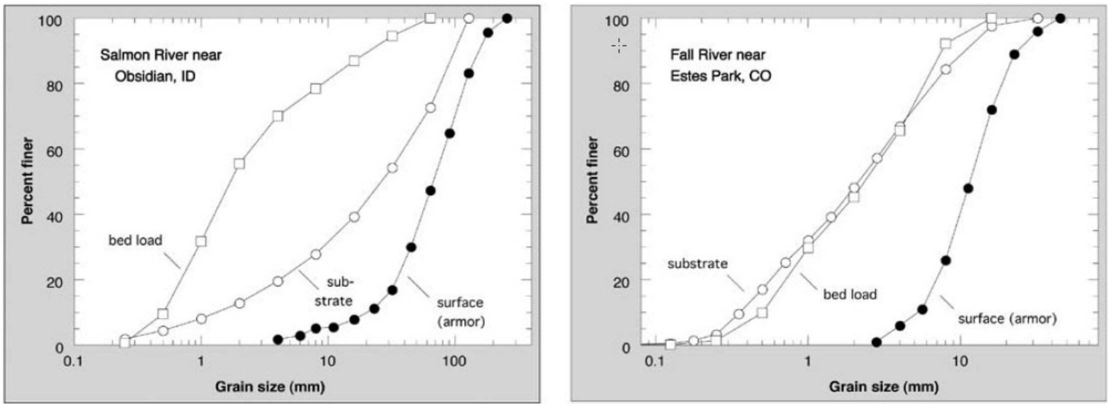


Figure 4-6 Graphical display showing the grainsize difference between the bedload substrate and surface layer (Pitlick et al., 2009).

BAGS software utilises six well-known bedload transport equations that have been developed specifically for gravel bedded rivers (Pitlick et al, 2009). As discussed in Section 2.5.5, the equations have been written into Microsoft Excel and run with a VBA script, so that a user interface requests specific data depending on the equation being utilised. In winter 2009 one of the primary developers and authors of the BAGS software was contacted to determine the applicability of the software to Tasmanian streams. The author advised (Pitlick, 2009, pers. comm.) that based on the photographs and information supplied, three of the six equations that BAGS incorporates, would be more suitable for my study sites. This was because the stream bed is comprised of coarse sediment and the difficulty in access prevents measuring the weight of bed material, required by inputs in other, less suitable, equations. These recommended equations therefore required only surface data inputs and includes:

1) surface-based equation of Parker (1990);
2) surface-based two-fraction equation of Wilcock (2001); and
3) surface-based equation of Wilcock and Crowe (2003) (Pitlick et al., 2009).

Equations 1 and 3 require inputs of channel cross section, reach-average water surface slope, discharge and bed surface grain size distribution. Equation 2 requires the sand and gravel fractions and a sample of bedload data (subsurface), the collection of which was outside the scope of this study. Therefore, equations 1 and 3 have been used for the purposes of estimating bedload transport within the catchment. Specific details on the data entry for both equations can be found in Pitlick et al., (2009). Bedload transport results are presented in Section 5.1.4.

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Chapter 5 Results

5.1 Fluvial Geomorphology

This chapter presents the results associated with the field data and desktop analysis described in the methods chapter. Results are initially presented from the qualitative field analysis data sheets showing the observations noted and the more basic field measurements. Quantitative methods on field hydrology, cross-sectional surveys, photographic analysis and bedload transport from empirical equations are then presented.

5.1.1 Visual Observations and Physical Form Analysis

Interpretation of API indicates that the inflows (reference sites) into Lake Augusta, the Ouse and James rivers, occur in broad flat valleys. Similarly, both rivers grade up into shallow valleys for sites 1-2 (Figure 5-1). Converse to this, the regulated reaches of the Ouse River flow from Augusta Dam in a shallow valley that closes into a steep gorge below site 7 (Figure 5-2), site 8 is located below this gorge. Compared with the lower sites (3-8) in the reference reaches of the upper Ouse River, sites 1 and 2 occur above a noticeable steep slope with a distinct section of bedrock control and bedrock steps separating sites 2 and 3. The most noticeable feature of the reference and regulated study reaches is a distinct lack in gravel-cobble bars. The rivers in this alpine setting lack in stream bar features and appear to simply function as a channel for transferring water. The presence of any bars merely represents higher areas of the stream bed that become exposed during low flows as opposed to bars created by lower inside bend velocities. Woody debris is unsurprisingly absent resulting from the lack of canopy vegetation being an alpine area. The streams within each sub-catchment have a relatively low gradient. The James River looses 43 m over the 7.01 km study area giving a mean slope of 0.01°, while the Ouse River reference reach looses 41 m over the 9.22 km study area also giving a mean slope of 0.01°. The Ouse regulated reach looses 84 m altitude over 9.99 km, which again equates to a slope of 0.01° The drop in altitude is typically associated with short rapids, cascades and steps within the channel that occur at all sites and act to dissipate stream energy. The steps are comprised of bedrock or boulders and occur over tens of metres rather than a gentle grade over kilometres.

 a  b

Figure 5-1 Reference sites 1 on the James (a) and Ouse River (b). Note the quadrat located over an exposed area of gravel-cobble in image b ready to photograph.

Figure 5-2 Near Ouse River regulated site 7 looking downstream toward the gorge.

The physical form data sheets were summarised and are presented in Appendix C. A general overview of these results is provided in Table 5-1. The results indicate that the reference sites occur within either broad or shallow valleys, while the regulated sites occur within a shallow to steep valley. The valley shape does not appear to significantly alter the floodplain features present as all sites exhibit an array of flood channels, floodplain scours or ponds; the latter particularly on the regulated sections of the Ouse River. It is note-worth that while there were no floodplain ponds recorded at the reference sites they still did occur, only less frequently than the regulated Ouse River sites. Bank shape and slope varies with site; however, steeper, more incised banks were more prevalent in the lower Ouse regulated sites. Some minor incision resulting in vertical or undercut banks was observed also in the Ouse reference sites, although the bank angle was generally low, compared with a moderate slope for the Ouse regulated sites (Table 5-1).

Mid-channel bars occurred throughout all sites, as did the presence of fine gravel build-up around obstructions, such as large boulders. Fish passage was variable amongst sites with the James River and Ouse regulated sites having more restriction than the Ouse reference sites. However, the lower Ouse regulated sites (OS5-OS7) has compounded issues for fish due to very hostile flow conditions that result from marked variability in dam operations (Figure 5-3d). This causes strong flow between bedrock and large boulders in the confined areas resulting in chute flow with high velocities or stepped flow over numerous cascades. This high velocity environment also influenced the compaction within the surface sediments. The Ouse regulated sites had fine gravels present but compared to the reference sites, gravels were more observed behind boulders (Figure 5-3c) and surface sediments showed a moderately packed to armoured layer. Rounded sediment dominated the Ouse regulated sites; however at least one site on both reference reaches contained dominantly angular or sub-angular material (Figure 5-3d). An example of a completed physical form data sheet is provided in Appendix C as a guide understanding each of the above observations. Other observations recorded but not considered below included channel modifications, local impacts, land use and visual water quality. These parameters were not included in Table 5-1 as there were no channel modifications, no ongoing stream impacts and there was an absence of visually discernible water pollution at all sites.


a


b


c


d

Figure 5-3 a) low velocity and b) high velocity discharge below Augusta Dam. c) sediment pockets hidden behind large boulders at Ouse regulated site 3 and d) angular small-large boulders at James reference site 8.

Table 5-1 Visual observations recorded summarised by study river

Study Site	Valley and Channel Shape	Floodplain Features and Width (m)	Channel Shape and Bank Slope	Bars Present	Sediment Compaction and Angularity	Dominant Flow Type and Reach Length (m)	Fish Passage (base-flow)
Ouse Reference	Shallow-broad valley with concave-lower bench channel	Flood channels, remnant channels, 147	Flat U shaped with low-steep vertical banks	Side and mid-channel both vegetated and unvegetated	Low to moderately compacted with rounded-well rounded particles	Riffle-glide, 287	Partly-moderately restricted
James Reference	Broad-shallow valley with concave-undercut channel	Flood channels, scours, 303	U shaped and widened with flat, Low and Moderate banks	As above but with bars around obstructions and high flow deposits	Low compaction with sub-angular-well rounded particles	Deep pool-run/riffle, 123	Very-moderately restricted
Ouse Regulated	Shallow-steep valley with concave-undercut channel	Flood channels, scours and ponds, 62	Flat U shaped with moderate-vertical banks	Side unvegetated and mid-channel unvegetated and vegetated	Moderate-packed with rounded particles	Shallow pool/riffle-cascade, 171	Very-moderately restricted

5.1.2 Hydrology and Cross Sections

Hydrology

Site gauging data measured during the field investigations on the 13th-14th March 2010 are shown in Table 5-2. Standard methods described in section 4.2.3 were followed (USGS, 2010). The hydrological data comparing sites J1 and J8 shows the typical relationship between a headwater step-pool stream and a lower gradient lower energy stream (Gomi, 2002; Vannote et al., 1980). As can be seen from Table 5-2, the upper reaches of the James River near J1 have a cross sectional area nearly 3.5 times smaller than the lower reaches of that river near Lake Augusta and a wetted perimeter and discharge approximately 1.5 times smaller. Conversely the velocity in the upper reaches of the James River is approximately 2.5 times greater than the lower reaches.

The Ouse River reference sites represent an order of magnitude greater discharge than the James River reference sites (Table 5-2). Furthermore, although the reference sites of both rivers represent similar distances from Lake Augusta, the notable differences comparing the upper and lower reaches of the James River are not observed on the Ouse River reference sites, the exception being velocity. The Ouse River reference sites show a 1.3 times increase in cross-sectional area from the upper site to the lower site, a 1.5 times increase in wetted perimeter, a minor increase in flow from local pick-up and a 1.3 times decrease in velocity at OR8 compared with the higher OS1 site.

There are three different hydrological sites for the Ouse River regulated reaches, the upstream and downstream sites as per other sub-catchments and an additional site Liawenee Canal (LC) shown to account for the off-take that occurs above site OS8. The data in Table 5-2 indicate that the main inflows to Lake Augusta (sum of J8 and OR8) equal 2.3439 cumecs, slightly less than the 2.4 cumecs being discharged over the same time period. The data in Table 5-2 shows that Liawenee Canal removes practically all flow from the Ouse River, with a velocity of only 0.001 m/sec being recorded below the Liawenee off-take. Also of note is a slight increase in flow (cumecs) between OS1 and LC, which indicates the flow contribution of the tributaries (e.g. Ibbots Rivulet) downstream of Augusta Dam.

Table 5-2 Hydrological Data from Field Gaugings for 13th – 14th March 2010 and from *Timestudio* (OS1 and OS8, including Liawenee Canal at Liawenee, LC) for the 14th March 2010 at 2pm.

Hydrological Data							
	Sites						
Parameter	J1	J8	OR1	OR8	OS1	OS8	LC
Area squ/m	0.709	2.5417	6.2005	8.1565	6.30	n/a	4.1
Wetted Perimeter (m)	4.67	7.77	13.32	19.85	13.40	n/a	9.3
Flow (Cumecs)	0.2166	0.3058	2.0001	2.0381	2.4000	n/a	2.8500
Velocity (m/sec)	0.31	0.12	0.32	0.25	0.38	0.001	0.38

The results in Table 5-2 show that the wetted perimeter and flow ratio from top to bottom sites is similar for both rivers, and although the actual figures are greater in the Ouse River, the scale of difference with the James River is similar. The ratio of flow between top and bottom sites for each of the reference rivers is likely attributable to the location of the gauging sites, because the upper James River sites show evidence of glacial ridges and moraines from between which, the water exits through small but confined ridges in a type of step-pool arrangement. The upper sites on the Ouse River, in contrast, occur in a broad valley with less confinement, evident by the order of magnitude increase in the cross-sectional area compared to the upper James River gauging site.

The obvious difference when comparing the regulated site flow from *timestudio* with flow from the field gaugings for site 8, is the difference between the OS8 and J8 or OR8 (Table 5-2). The data are showing that essentially all of the flow released below Augusta Dam is being extracted from the Ouse River at the Liawenee Canal off-take and transferred to Great Lake. The Liawenee Canal therefore acts as a second point of regulation on the Ouse River. In order for flow to pass below the Liawenee off-take the flow entering from upstream needs to be greater than the carrying capacity of Liawenee Canal or due to temporary closure of Liawenee Canal (e.g. for maintenance). To further explore the hydrology of this area flow data were obtained for Lake Augusta discharge valves, Lake Augusta Spillway, Liawenee Canal at Liawenee and Ouse River below the Liawenee Canal off-take (Ouse River regulated site 8). The flow data was plotted in Microsoft Excel for each parameter and is shown in Figure 5-4a-d. Data from the Augusta Dam valve has only been available since 13/04/2005, but this shows that nearly all of the flow is captured and transferred to Great Lake via Liawenee Canal (Figure 5-4a and b). By comparison Figure 5-4c and d shows that with the exception of a small amount of base-flow the Ouse River below Liawenee Canal only receives flow during a spill event at Lake Augusta.

Stream Cross Sections

At each of the gauged sites cross-sections were completed to complement the stream hydrology and to provide an indication of bank shape. Channel profile is shown in the cross-section plots in Figure 5-5. Channel profiles have been plotted with the altitude on the y-axis and the absolute location of the survey staff on the x-axis. Absolute location was plotted as these points represented the location of visually discernible alterations to stream bed profile. The cross-sections indicate that there is little change in the bank-full width of the James River, although there is a notable increase in the channel depth. The Ouse River reference cross-sections indicate that there is an increase in both channel width and depth when comparing site OR1 with OR8 (Figure 5-5).

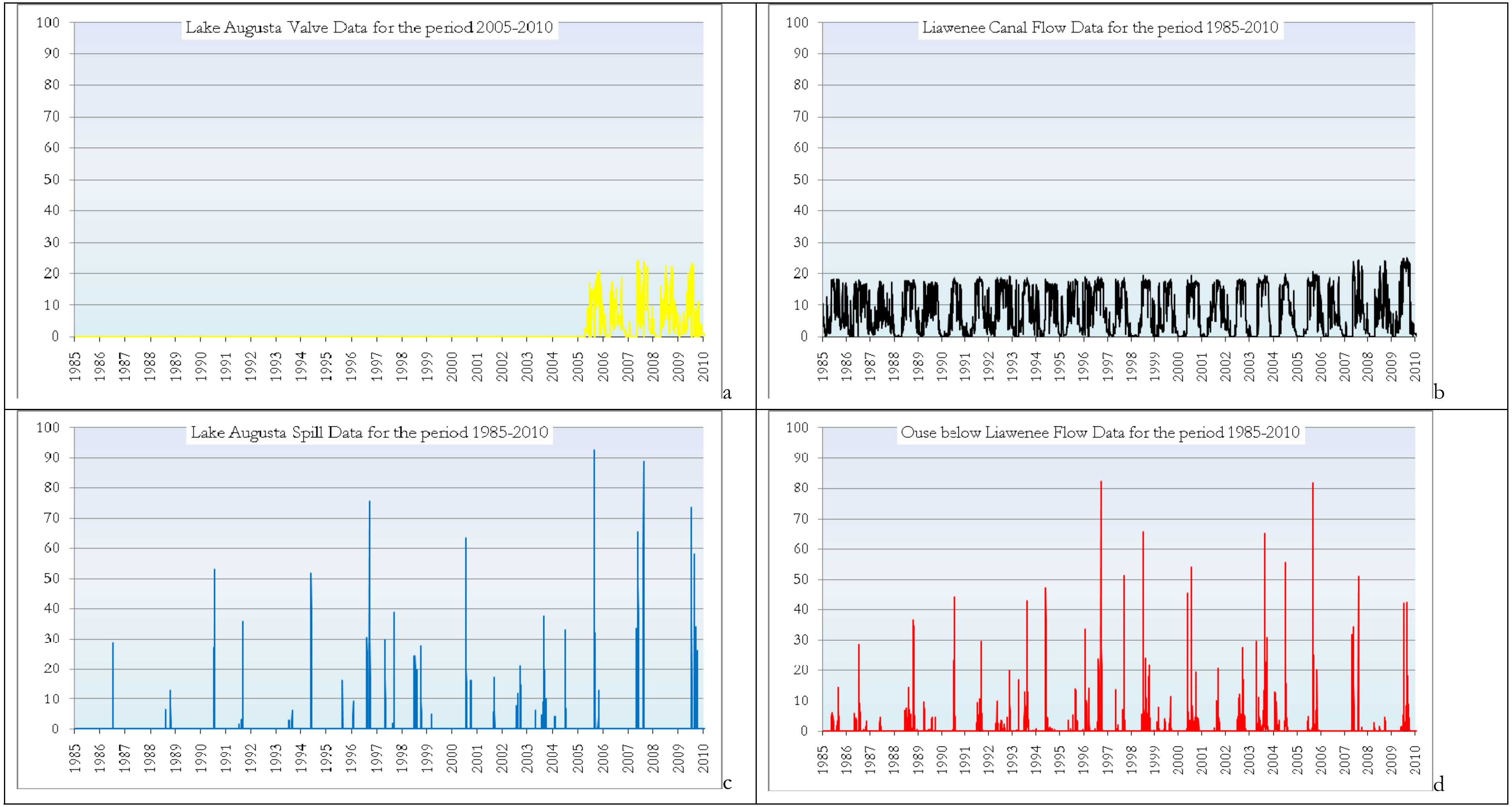


Figure 5-4 Flow releases (in cumecs) for a) Lake Augusta Dam valve, b) spillway, c) Liawenee Canal and d) Ouse River below Liawenee Canal

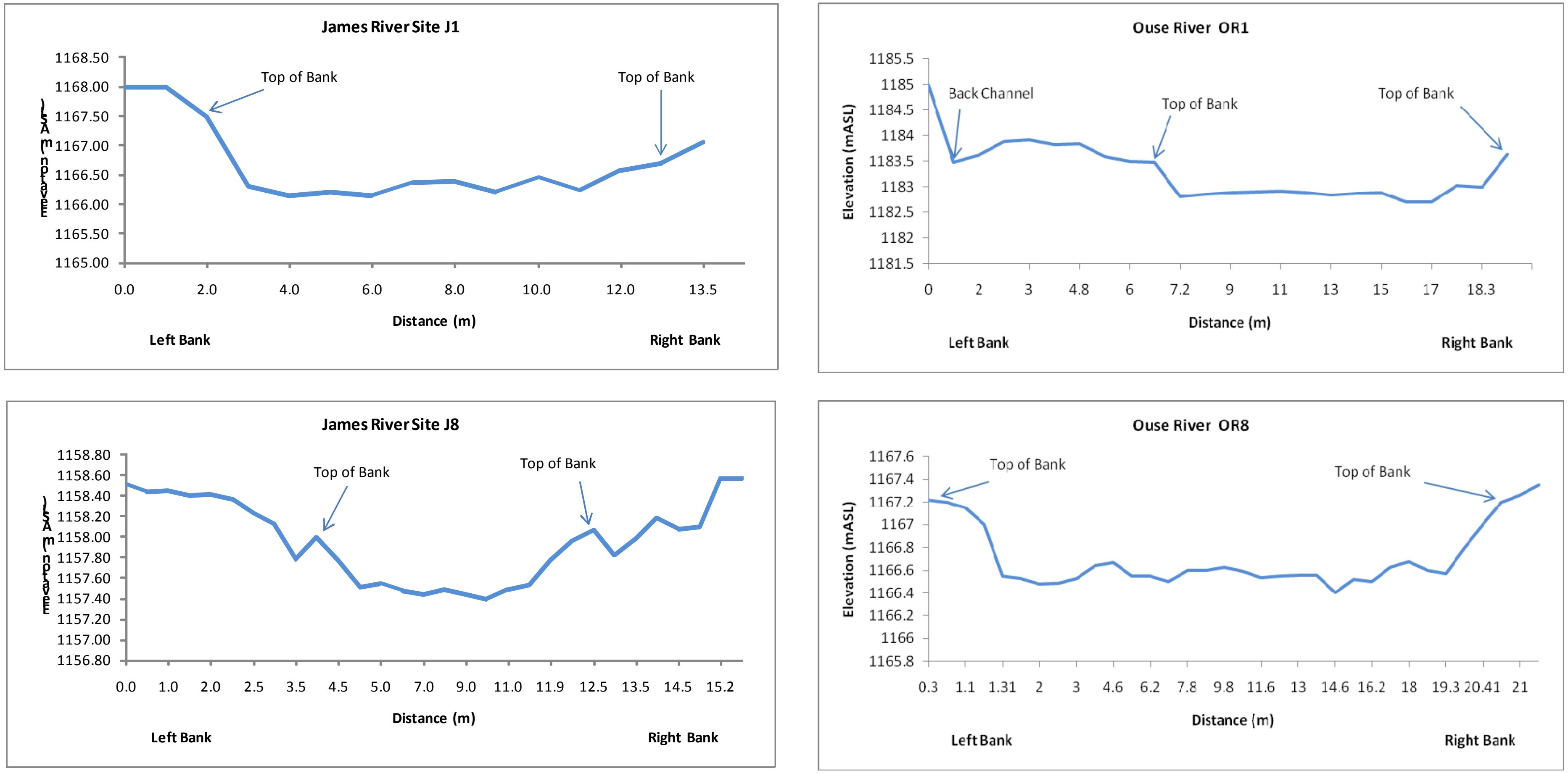


Figure 5-5Channel cross-sectional profiles at upstream (sites 1) and downstream (sites 2) reference sites

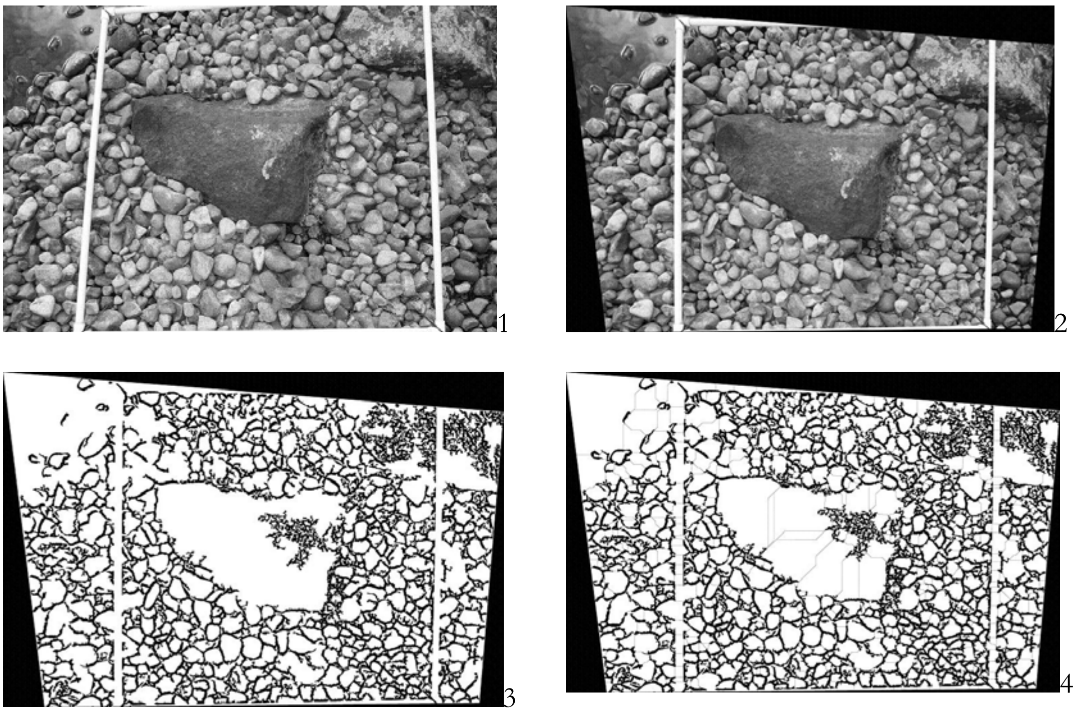
5.1.3 Image Processing and Analysis

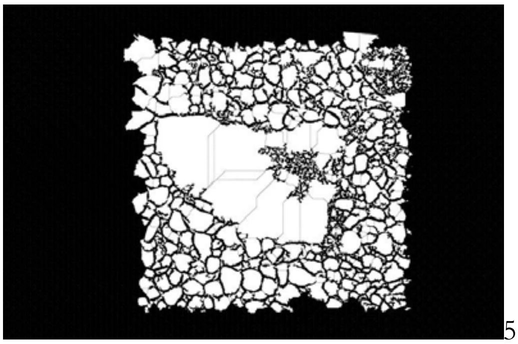
Image Results

Photographs analysed using Digital Gravelometer™ that had a visual match (Table 4-3) of 5 or better were used for further analysis. All reference and regulated sites had a fairly even spread of images with a visual rating of either 8 or 9. No images received a visual rating of 10 as there was always splitting or clumping of at least a few grains within an images. Out of all the images analysed, 11 sites received a visual rating of 5 (Appendix B).

The Digital Gravelometer™ software provides six output options when processing an image. These are shown in Figure 5-6 and include:

1. greyscale conversion,
2. greyscale transformed (rectified),
3. individual grains selected,
4. greyscale image overlaid on grains selected,
5. final grains selected,
6. greyscale image overlaid on grains selected (Loughborough University Enterprises Limited, 2006)




5

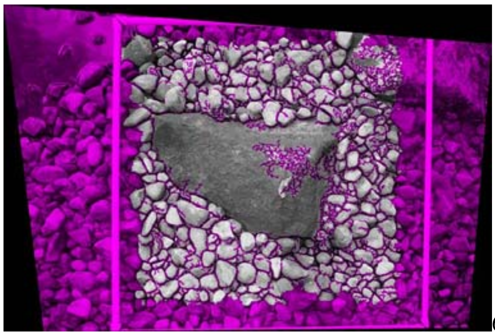

6

Figure 5-6 Six output options for viewing the image processing stage in Digital Gravelometer™.

The results of the image processing shown in Figure 5-6 are for IMG_0535, which is site 2 on the James River. The image was given a visual match rating of 8 as most of the digitising was performed well with the exception of the top of the centre boulder, which has been over digitised with fine sediment. The boulder was in fact free of sediment and it was lichen that was digitised incorrectly. A truncation of 8 mm was recommended for this image which removed most of this source of error. Other examples of visual rating matches are shown in Figure 5-7. The images shown in Figure 5-7 all had different scores rated on how well each image was digitised against visual observation of match. Image a is IMG_0840 from Ouse reference site 5 and scored 5 due to over-digitising a large grain into small grains; image b is IMG_3549 from Ouse regulated site 4 and scored 7 as most of the fine and large grains were detected, although some over digitising occurred; image c is IMG_0519 from James reference site 5 and scored 9 due to most of the small grains being correctly digitised. image d is IMG_0548 from Ouse reference site 2 and scored 6 as the software experienced difficulty in digitising the small grains and continued to split some into smaller grains. Grain size distributions for the images shown in Figure 5-7 were calculated using the Digital Gravelometer™ software and are shown in Figure 5-8.

Distributions are plotted as cumulative percent finer than on the Y axis and the grain size in millimetres on the X axis. Despite the small size of the graphs the intent is to show how a visual image with identified grains translates into a graphical portrayal of grain size distribution. Figure 5-7a and b shows that images containing large cobbles and boulders cause more difficulty with the software processing than do images containing fine sediment present (Figure 5-7c and d. Comparatively, the graphs in Figure 5-8 shown the same graphical representations of the image processing results in Figure 5-7. Figure 5-8a shows a coarse grain size distribution, absent of most fine sediment, matching what is visually observed in Figure 5-7a. Figure 5-8b again shows a coarse proportion of sediment, but this time with an increase in fine sediment and aligns visually with Figure 5-7b. Figure 5-8c shows a dominance of fine sediment between 8 mm and 32 mm aligning well with grains that are visually observed in Figure 5-7c. Finally, Figure 5-8d similar to Figure 5-8c shows a dominance in the fine sediment, but this time with the larger grain being identified; this also aligns well with the comparison between the images in Figure 5-7d and Figure 5-7c. Therefore the images in Figure 5-7 and the graphs in Figure 5-8 show that despite some variability in the quality of visual match, truncating the sediment and adjustments in the Digital Gravelometer™ software result in relatively accurate representations of the grain size distribution within each quadrat.

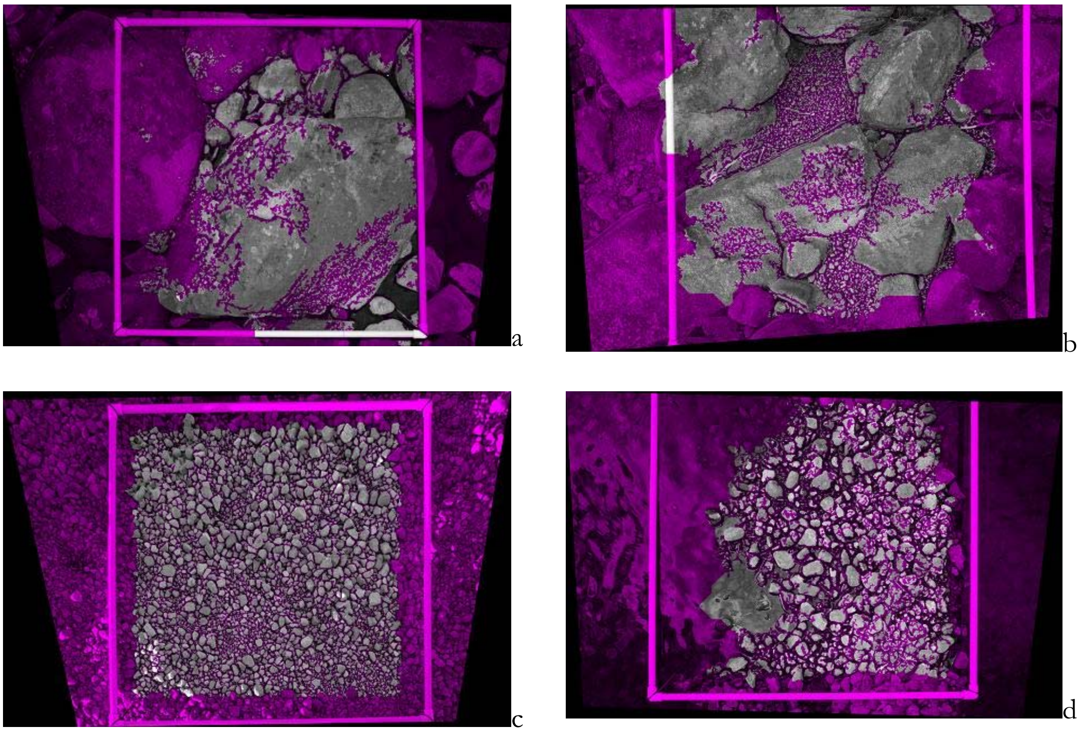
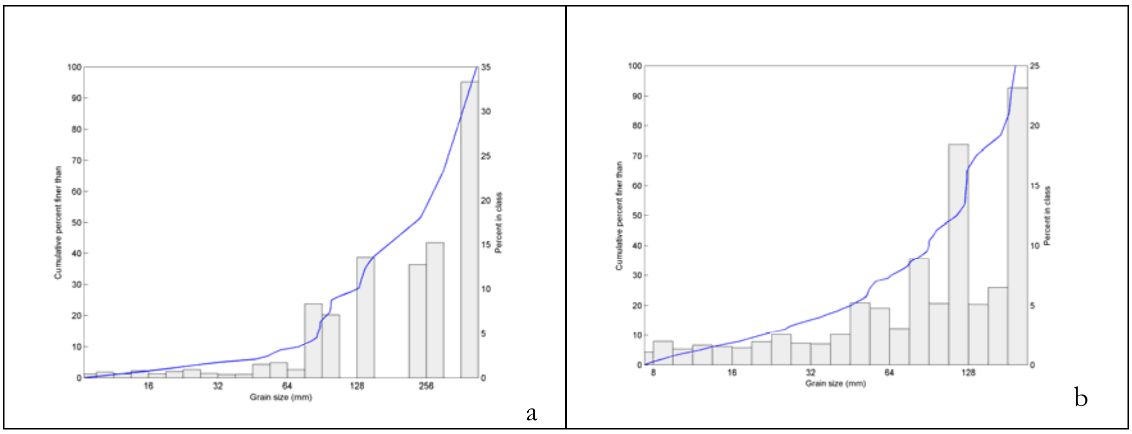


Figure 5-7 Examples of different visually rated image outputs from Digital Gravelometer™.



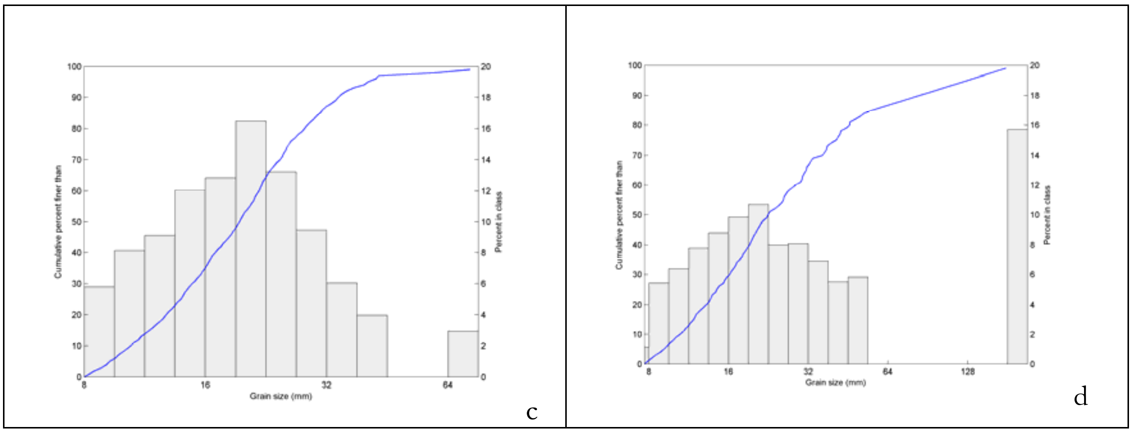


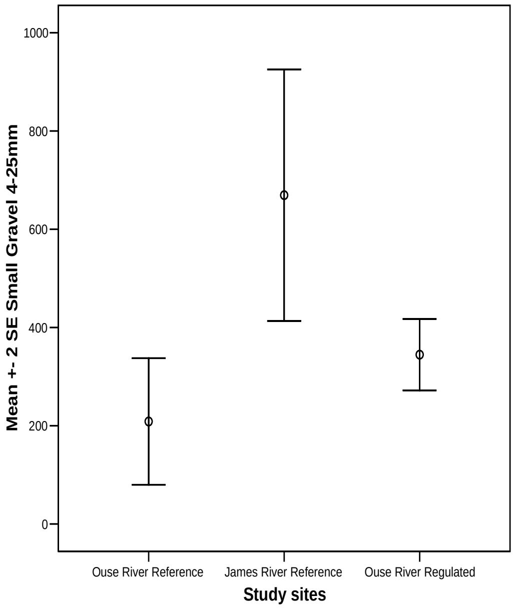
Figure 5-8 Grain size distribution plots showing percent finer than verses grain size (mm)

Statistical Analysis

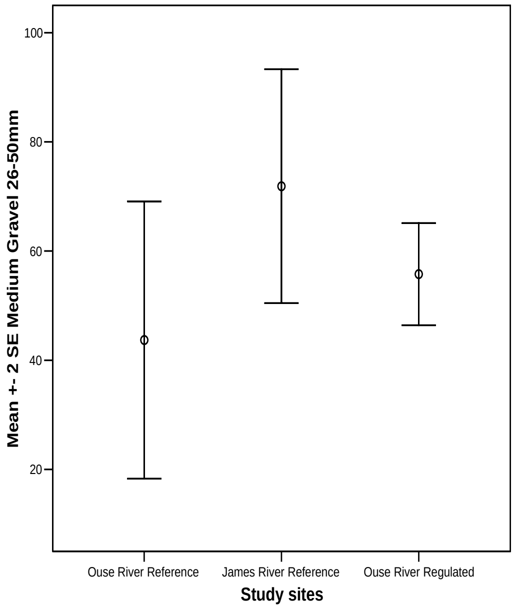
Results for the statistical analysis on the exported data from the Digital Gravelometer™ were analysed in two ways firstly by including only the highest visually rated images for each site only and secondly, by including all remaining images. However, only one useable image was for some sites due to poor grain recognition by the Digital Gravelometer™ software. Due to the element of bias this introduced, the standard error bars for 'selected images only' is included as

which shows a slight reduction in data extent for some size classes (e.g. the 226-300 mm size class has zero data for the Ouse River regulated site, while the inclusion of all data shows the presence of standard error). The results for the complete dataset are included below.

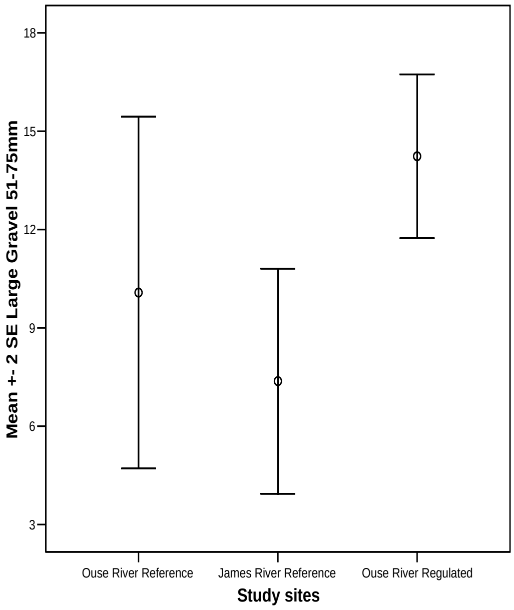
SPSS was used to graph standard error to review the variation in the data set. The standard error bars are shown in Figure 5-9. As can be seen from each of the seven graphs in Figure 5-9, each graph shows one grouping of sediment size class and compares the data between each of the sub-catchments.


Mean +- 2 SE Small Gravel 4-25mm
1000
800
600
400
200
0
Ouse River Reference
James River Reference
Ouse River Regulated
Study sites

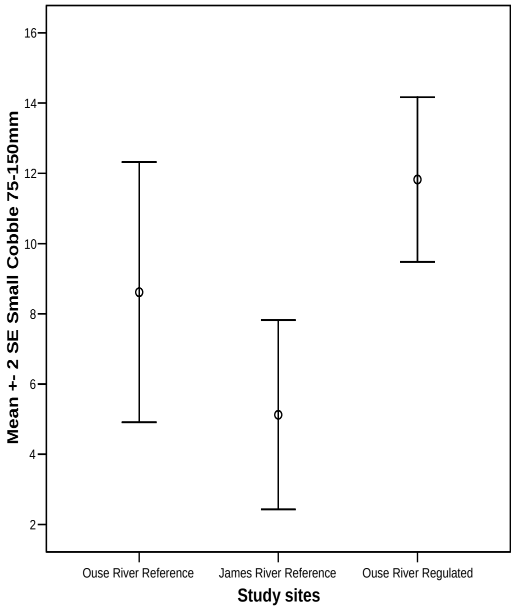
a


Mean +- 2 SE Medium Gravel 26-50mm
100
80
60
40
20
Ouse River Reference
James River Reference
Ouse River Regulated
Study sites

b


Mean +- 2 SE Large Gravel 51-75mm
18
15
12
9
6
3
Ouse River Reference
James River Reference
Ouse River Regulated
Study sites

c


Mean +- 2 SE Small Cobble 75-150mm
16
14
12
10
8
6
4
2
Ouse River Reference
James River Reference
Ouse River Regulated
Study sites

d

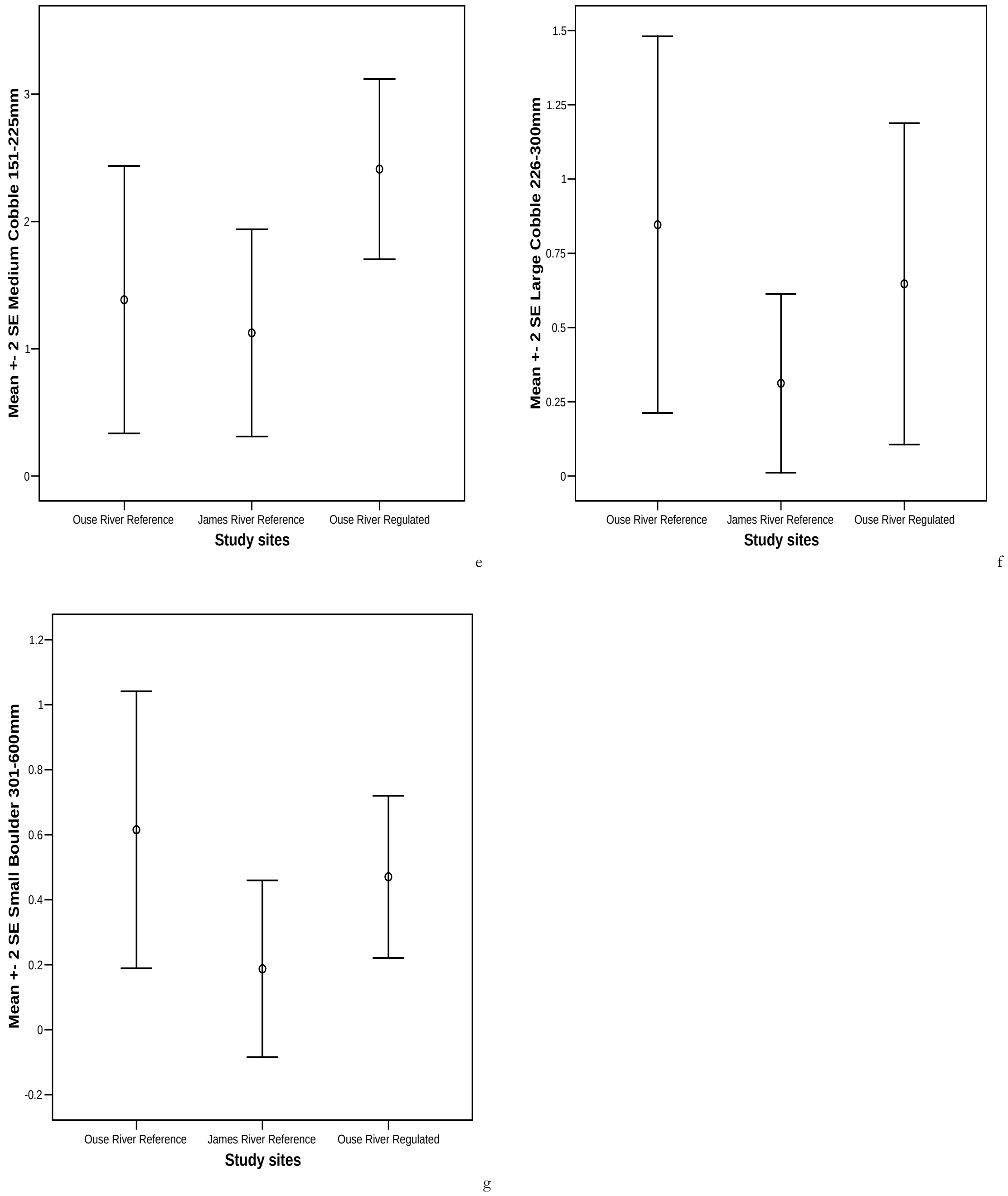


Figure 5-9 Standard Error bars for each of the sediment size classes comparing each sub-catchment. Size classes represented are in mm and include a – 4-25, b – 26-50, c – 51-75, d – 76-150, e – 151-225, f – 226-300 and g – 301-600.

The standard error bars shown in Figure 5-9 do not show large variations within the sub-catchments, with typically at least two sub-catchments appearing to fall within similar values. The data does show that results from some sites do not overlap, possibly indicating some significant differences (Dytham, 2003). The data also showed that there was no sediment in the

0-3 mm size class, as most data was truncated to remove all sediment finer than ~8 mm, due to the Digital Gravelometer™ software recommendation. Fine sediment (<8 mm) has shown to be transported in significant quantities and form an important part of bedload transport in one study (e.g. Bond, 2004); therefore, omitting this data does limit the current study . Furthermore, there were no data recorded within the <601 mm category for any of the sites. This is not to say that there was not sediment >601 mm, for there was sediment greater than this size class observed, but rather it reflects the fact that the software is primarily aimed at the finer groupings below this category. It is necessary to mention that with the inclusion of the complete dataset there are some sites within each sub-catchment that only had one successful photo to export data from, thus creating an unbalanced design.

To determine if any statistical differences were present, a one-way ANOVA test was completed. Before this test could be completed the homogeneity of variance test was completed. This revealed that there were no issues with violating the assumptions of ANOVA. The null hypothesis (H_0) to be tested is that there is no significant variance in the means between sites in each of the sediment classes. A statistically significant result, the hypothesis (H_1), occurs when the *P*-value is less than 0.05, inferring that there is only a 5% chance that a difference does not occur. The one-way ANOVA test on all sites revealed that there is a statistically significant difference between sub-catchments for three of the sediment classes as shown in Table 5-3 under the 'Sig.' heading. Therefore H_0 is rejected and the hypothesis (H_1) that a statistical difference exists between the sites is accepted.

Table 5-3 One-way ANOVA test to determine if a significant difference between sediment classes occurs between sub-catchments.

Sediment Class	Comparing	Sum of Squares	df	Mean Square	F	Sig.
Small Gravel 4-25mm	Between Groups	1671112.570	2	835556.285	7.281	.002
	Within Groups	4934815.887	43	114763.160		
	Total	6605928.457	45			
Large Gravel 51-75mm	Between Groups	394.377	2	197.188	3.759	.031
	Within Groups	2255.732	43	52.459		
	Total	2650.109	45			
Small Cobble 76-150mm	Between Groups	369.855	2	184.927	5.920	.005
	Within Groups	1343.298	43	31.239		
	Total	1713.152	45			

The ANOVA testing only states that there is a difference, not where the difference occurs, thus a post-hoc test is required to determine where the difference occurs. The Tukey HSD and LSD post-hoc tests that were utilised revealed some interesting differences. Table 5-4 shows the results for only those categories that were statistically significant in the Tukey HSD test. The Tukey HSD and LSD tests are essentially similar in principle, however, they manipulate the data in different ways. The LSD test uses the logic that if only the significantly different results are compared there is no need to reduce the critical *P*-value below 0.05 for paring comparisons (Dytham, 2003). This statement is interesting, as the LSD test identified significant results for two additional groups not previously showing significant variations with ANOVA in Table 5-3. Based on the cautionary use of the LSD testing on non-statistically significant results, the Tukey HSD results are preferred and are presented in Table 5-4. Table 5-4shows the three sediment classes that were identified in the one-way ANOVA test (Table 5 4); the significant differences between sub-catchments can now be identified. The mean difference column (I-J) gives the difference between the mean values and an '*' indicates that there is a significant difference between the means (Dytham, 2003). The 'Std. Error' provides an estimate of the mean differences for the whole analysis and the 'Sig.' shows whether or not a significant difference occurs between the pairs being compared. The final two columns show confidence intervals for the difference – when the two columns have the same sign (+ or -) then the two groups will be statistically different (Dytham, 2003).

The small gravel class (4-25 mm) in Table 5-4 shows that there is a very significant (P=0.002) difference between the Ouse River reference and the James River reference sites and a significant difference between the James River reference and the Ouse River regulated sites. The results for large gravel (51-75 mm) indicate that a significant difference occurs between the James River reference and the Ouse River regulated sites. Similarly, the small cobble size class (76-150 mm) shows a very significant difference occurs again between the James River reference sites and the Ouse River regulated sites.

Table 5-4 Post-hoc Tukey HSD test results comparing sub-catchments by sediment classes; statistically significant (P=<0.05) results are in bold.

Dependent Variable	Test Method	(I) Study sites	(J) Study sites	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Small Gravel 4-25mm	Tukey HSD	Ouse River Reference	James River Reference	-460.558(*)	126.494	**.002**	-767.61	-153.50
			Ouse River Regulated	-135.896	124.815	.526	-438.88	167.08
		James River Reference	Ouse River Reference	460.558(*)	126.494	**.002**	153.50	767.61
			Ouse River Regulated	324.662(*)	117.998	**.023**	38.23	611.09
		Ouse River Regulated	Ouse River Reference	135.896	124.815	.526	-167.08	438.88
			James River Reference	-324.662(*)	117.998	**.023**	-611.09	-38.23
Large Gravel 51-75mm	Tukey HSD	Ouse River Reference	James River Reference	2.702	2.704	.581	-3.86	9.27
			Ouse River Regulated	-4.158	2.669	.275	-10.64	2.32
		James River Reference	Ouse River Reference	-2.702	2.704	.581	-9.27	3.86
			Ouse River Regulated	-6.860(*)	2.523	**.025**	-12.98	-.74
		Ouse River Regulated	Ouse River Reference	4.158	2.669	.275	-2.32	10.64
			James River Reference	6.860(*)	2.523	**.025**	.74	12.98
Small Cobble 76-150mm	Tukey HSD	Ouse River Reference	James River Reference	3.490	2.087	.227	-1.58	8.56
			Ouse River Regulated	-3.208	2.059	.275	-8.21	1.79
		James River Reference	Ouse River Reference	-3.490	2.087	.227	-8.56	1.58
			Ouse River Regulated	-6.699(*)	1.947	**.004**	-11.42	-1.97
		Ouse River Regulated	Ouse River Reference	3.208	2.059	.275	-1.79	8.21
			James River Reference	6.699(*)	1.947	**.004**	1.97	11.42

Non-metric multidimensional scaling (MDS) was then used to configure each of the sites and plots the sites based on a matrix of the similarity or dissimilarity between each site (Clarke and Warwick, 2001). Figure 5-10 shows the 2-dimensional MDS ordination of the relative site data based on square-root (√√) transformed counts within each sediment class and the Bray-Curtis similarity matrix (Clarke and Warwick, 2001).

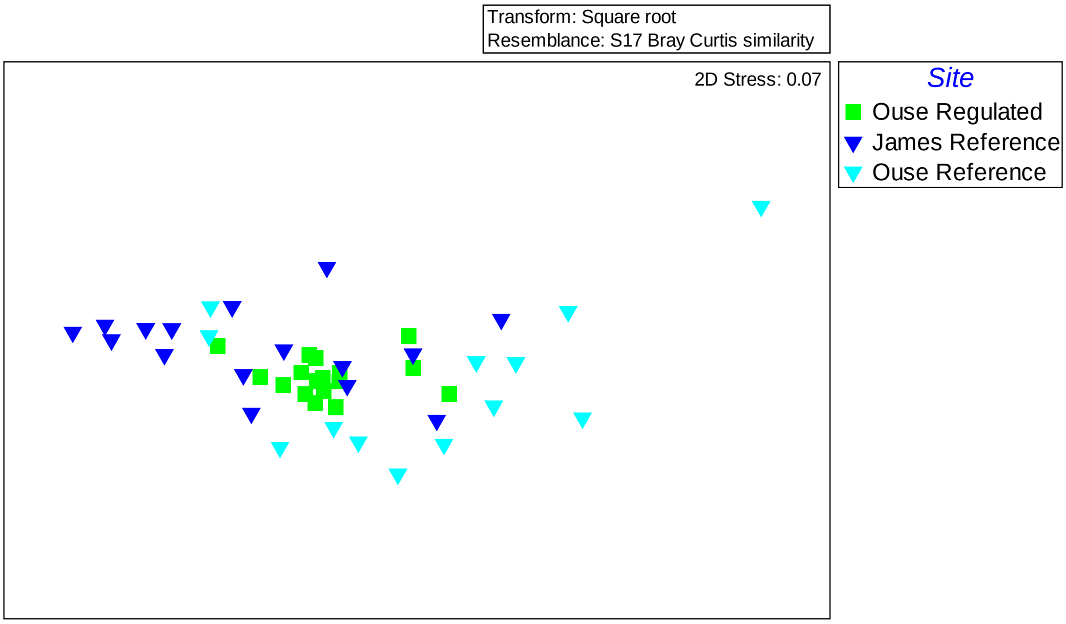


Figure 5-10 MDS ordination of the 46 photographic quadrats based on √√-transformed counts within each sediment class and Bray-Curtis similarities (Stress = 0.07).

The ordination plot in Figure 5-10 corresponds to a good ordination (stress <0.1) with no real prospect of a misleading interpretation that might have resulted from PRIMER having to recalculate the position of points in a manner that would produce a high stress value (stress >0.2) and low validity in the results (Clarke and Warwick, 2001). The results shown in Figure 5-10 show that there is relative spread in the Ouse and James reference sites with a degree of overlap present. The Ouse reference sites appear to have a slightly wider spread of data than the James reference sites, while the Ouse regulated sites show a greater degree of clustering within the sub-catchment indicating limited variability between sites (Figure 5-10).

The outlying result for the Ouse reference sites (top right of Figure 2-8) was investigated to determine why this site might be placed differently from other sites. The outlying point represents IMG_0854_Ouse 8. To elucidate why this site has been separated the final image overlay from Digital Gravelometer™ was investigated and is shown in Figure 5-11.

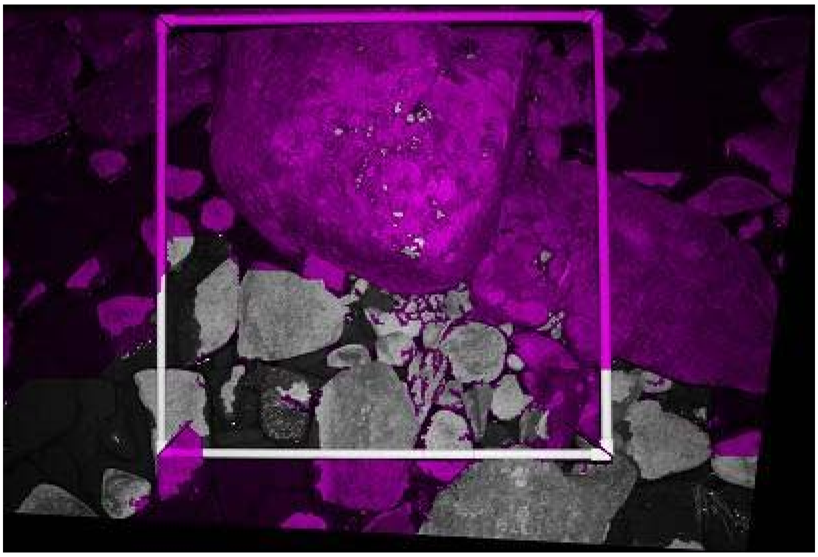


Figure 5-11 Final image overlay from Digital Gravelometer™ for Ouse Reference site 8 IMG_0854.

As can be seen from Figure 5-11 the image has excluded approximately 50 % of the grains resulting in a smaller sampling area; furthermore, the quadrat has been digitised (shown by the un-highlighted areas) and sediment beyond the quadrat has been included. Despite these issues the grains included and excluded for the most part, have boundaries that are correctly digitised. The image was given a visual quality match of 5 due to half the image being excluded. The included digitised grains visible on the excluded main boulder would not have influenced the results as the image was truncated at 10.5 mm, thus removing most of this fine and incorrectly digitised sediment. It is likely that the lack of any fine sediment at this site is the reason why IMG_0854 occurs as an outlier.

The next stage of site analysis involved determining the factors that contribute to the similarity within the sites. To assess the similarity *within* each sub-catchment the SIMPER analysis in PRIMER, similarity percentages index, was used. SIMPER is an exploratory analysis that indicates which groups are responsible for either a clustering pattern or a spread within each group (Clarke and Warwick, 2001).

Table 5-5 Percent contribution of sediment classes to over-all similarity using SIMPER analysis in PRIMER

Group	Contribution %	Average Similarity%
Ouse Regulated		86.59
Small Gravel 4-25 mm	52.74	
James Reference		73.70
Small Gravel 4-25 mm	63.64	
Ouse Reference		66.54
Small Gravel 4-25 mm	51.19	

The data in Table 5-5 shows that the Ouse regulated group of photo transects are the most similar (i.e. least variation in sediment counts along the river between sampling points). The distinguishing factor that accounted for this similarity was primarily the count of small gravels 4-25 mm, which contributed to over 50 % of the similarity in site comparisons for the Ouse River regulated sub-catchment.

The opposite of this test, and a more likely useful measure of differences, is the dissimilarity percentages index in PRIMER; which by disaggregating the samples, most precisely identifies the classes responsible for the arrangement in the MDS ordination (Clarke and Warwick, 2001). Table 5-6 shows the dissimilarity comparisons *between* sites for each of the sub-catchments. Only the primary contributor to the dissimilarity has been included as it accounts for nearly 50 % of the differences in all sub-catchments. The medium gravel (26-50 mm) fraction was the next group responsible for the dissimilarity between sites; however, this only accounted for 14-21 % of the difference between sub-catchments and was not shown to be statistically significant Table 5-4. shows that it is the fine gravel that accounts for the dissimilarity between the sites, accounting for no less than 49.85 % of the difference between the Ouse regulated and Ouse reference sites. The highest dissimilarity between the sites occurred in the 4-25 mm size class between sites James reference and Ouse reference sites with an average dissimilarity of 35.54 % and a contributing percentage of 57.92 %. This difference is visible in the mean standard error bars for the 4-25 mm size class in Figure 5-9.

Table 5-6 Percent contribution of sediment classes to over-all dissimilarity using SIMPER analysis in PRIMER

Groups	Contribution %	Average dissimilarity %
Ouse Regulated & James Reference		23.40
Small Gravel 4-25 mm	53.76	
Ouse Regulated & Ouse Reference		27.75
Small Gravel 4-25 mm	49.85	
James Reference & Ouse Reference		35.54
Small Gravel 4-25 mm	57.92	

5.1.4 Sediment Transport (BAGS)

Bedload transport was calculated using two surface-based equations, namely the,

- Surface-based bed load equation of Parker (1990); and
- Surface-based relation of Wilcock and Crowe (2003)

These equations were recommended for use within the current study by one of the BAGS software developers (John Pitlick, pers. comm.., 2009). Input data was sourced from the Digital Gravelometer™ outputs, cross-section results, discharge calculations, reach average water slope calculated from a digital elevation model and Manning's *n* after Simons and Richardson (1966). The results of the bedload transport equations are shown in Table 5-7. Results for the Ouse regulated sites were calculated on an arbitrary 2.5 cumec Augusta Dam discharge, the discharges used in the BAGS calculations for the reference sites were based on the results in Table 5-2. A Manning's *n* of 0.04 was used for all sites as this represents a small stream with low slope on plains at less than bankfull stage and the slope for all sites was 0.01°.

The results in Table 5-7 show extremely low rates of bedload movement with the Ouse reference site 1 likely to produce the largest volume of sediment at 0.1 g/min shown under the Wilcock and Crowe (2003) method; however the same data under the Parker method shows several orders of magnitude less bedload transport. The results are displayed as E-09 indicating that the decimal point needs to be moved 9 places into the negative, as is the case for James reference site 8 under the Wilcock and Crowe (2003) surface based transport equation. Experimentation by increasing the slope and discharge greatly increased the sediment transport rates to ranges within 0.1 kg/min – 1.5 kg/min; however, yielded incorrect results as the inputs did not represent true environmental parameters and were only undertaken to cross-check the low results shown in Table 5-7.

Table 5-7 Bedload transport rates for all study sites

Site	Discharge as kilograms / minute	
	Parker (1990)	*Wilcock and Crowe (2003)*
James reference 1	2.0823E-08	3.67474E-05
James reference 8	2.13925E-14	8.94499E-09
Ouse reference 1	8.79347E-06	0.000100573
Ouse reference 8	7.78815E-13	5.05053E-07
Ouse regulated 1	2.0823E-08	3.67474E-05
Ouse regulated 8	7.95886E-11	1.48715E-06

Table 5-8 is the same format as Table 5-7 only this time the range of normalised shear stress (τ) values, (discussed in Section 2.5 Calculating Bedload Transport) and the mean grain size diameter +/- one standard deviation. The most noticeable result from Table 5-8 is the greater τ values at top sites (number 1 sites) and a lower grain size mean, compared to the bottom sites (number 8 sites), which have lower τ values and greater grain size means. Re-examining the data in Table 5-7 reveals that this decrease in shear stress and increase in grain size means correlates to a decrease in sediment transport on a longitudinal scale between sites 1 and 8.

Table 5-8 Normalised shear stress values and mean grainsize distributions for sites where sediment transport rates were calculated

Site	Range of Shear Stress (τ) from BAGS	Corresponding Grain Size Distributions (mm)		
		D_{16}	D_{50}	D_{84}
James reference 1	0.264 – 0.275	11.5	23.4	71.8
James reference 8	0.109 – 0.118	13.0	30.2	105.4
Ouse reference 1	0.309 – 0.415	11.0	20.3	38.0
Ouse reference 8	0.131 – 0.136	64.1	221.4	352.0
Ouse regulated 1	0.264 – 0.275	11.5	23.4	71.8
Ouse regulated 8	0.177-0.188	16	30.7	86.7

Chapter 6 Discussion

6.1 Fluvial Geomorphology and General Observations

In order to assess each of the sub-catchment areas to determine their suitability as reference and regulated sites the fluvial geomorphology of each study site was recorded. The aims of comparing the sites and sub-catchments were, firstly to determine whether the sub-catchments were suitable for a comparative study (Best et al., 2003), and secondly, to identify key features that control stream processes and, how the presence of Augusta Dam may influence stream processes and thus downstream ecological health (Massey, 2007). The latter requires an understanding of the difference between the sediment composition within each sub-catchment.

The dominant proportion of valley shape at all study sites was found to fall within a broad-shallow valley with colluvial material and cascades in the upper sites, as opposed to the step-pool to riffle-run sections in the lower sites that exerted the greatest control on energy dissipation. Below Augusta Dam there was a slight dominance in riffle-pools in the more upstream sites and cascade-chutes before the gorge section upstream from the lowest site. Altitudinal differences were minor, varying from 41-84 m over lengths ranging from 7-10 km in length, thus giving a low grading slope of 0.01° for all sub-catchments. All sites had a flattened U-shape stream channel cross-section, banks were more variable, with some vertical under-cutting banks being present on the Ouse reference and regulated sites, while the James reference sites tended to have low-moderately sloping banks and greater floodplain connectivity. Other parameters recorded are shown in Table 5-1. Vegetation lines the banks in most sites and creates local roughness, while the colluvial and riffle sections create localised sites for sediment storage, as has been observed in other studies (Gomi, 2002).

Catchment size and water holding capacity (lakes and tarns) was investigated to assess how similar each sub-catchment is on a spatial scale. Table 3-1 indicates that the James and Ouse River sub-catchments are almost identical in size, but the waterbody surface area is double in the James River sub-catchment with 8 km^2 of water surface area, while the Ouse reference sub-catchment has 4 km^2 of water surface area. Comparably, the Ouse regulated sub-catchment has a water surface area equivalent to both reference sites combined, a result that is unsurprising given the presence of Lake Augusta. The Ouse regulated sub-catchment area is also ~20 km2 larger than each of the two individual reference sub-catchments. Information on the catchment size and physical properties indicates therefore, that the sub-catchments are comparable.

To further investigate catchment similarities, the hydrological discharge at the most upstream and downstream reference sites were measured to determine if any flow differences existed (Table 5-2). The resulting data indicated that the James reference sites had an order of magnitude lower flow than the Ouse reference sites, and Section 3.4 and 3.5 indicated that this may be due to the underlying geology and past glacial re-shaping of the landscape. These headwater streams typically store flows in side channels, ponds and to groundwater (Gomi, 2002). Stream power was typically low and increased flows during winter were observed to quickly pass bankfull, flooding ponds and engaging side channels. While deep pools were observed in the reference reaches they were not frequent. There were very few deep pools present throughout the regulated sites; however, low stream power is known to limit pool development (Davies et al., 2005b).

Channel cross-sections were also measured at each of the reference sites to compare sites and determine if they fitted the typical trend of downstream widening (Church, 1992). The channel cross-sections (Figure 5-5) indicated distinct trends of downstream widening and identified some similarities between sites, such as the presence of backwaters/side channels and flat shallow bottoms. Therefore, the results of the visual observations, stream and catchment hydrology and cross-sections together indicated that there were sufficient similarities between each sub-catchment to make them suitable as comparative reaches in order to further assess whether any statistically significant differences occur between reference and regulated reaches.

6.2 Alterations to Sediment Composition and Potential Causes

The basis of the comparative study was, firstly, to assess differences between the sub-catchments by comparing the grain size distribution of the stream sediment within each sub-catchment, and secondly determine whether there are differences in the sediment composition and how any difference may influence that sub-catchment. The results of the image processing (Table 5-4) provided a statistically significant result (P=<0.05) for three sediment classes, namely the 4-25 mm, 51-75 mm and the 76-150 mm, when data were analysed using a Tukey HSD post-hoc test. In the 4-25 mm size class the Ouse reference was shown to be significantly different (P=0.002) from the James reference sites and the James reference sites significantly different (P=0.023) from the Ouse regulated sites. Figure 5-9a shows that this reflects the James reference sub-catchment, which contains both a large volume and spread of small gravel throughout its sites. The Ouse reference contains fewer small gravels but a moderate spread, while the Ouse regulated reach has a moderate proportion of fines (compared to the reference sites) but limited variability between sites, especially when compared to the James reference sites. Analysis of the large gravels component (51-75 mm) also showed a statistically significantly different result (P=0.25) between the James reference and the Ouse regulated. Figure 5-9c shows that overall there are relatively low rates of large gravel between the three sub-catchments, and while the Ouse regulated sites contain larger volumes, it is the inter-site diversity that separates this site from the other two reference sites, which contain more of a spread amongst each site. The final component where a significant difference (P=0.004) was revealed was the 76-150 mm group and was between the James reference sites and the Ouse regulated sites. The differences in Figure 5-9d show that, similar to the previous component, the Ouse regulated sub-catchment contains a greater number of small cobbles with slightly reduced variability comparative to the James reference sub-catchment.

To further explore these differences an MDS ordination plot was constructed (Figure 5-10) that clearly shows the spread of data. Multivariate analysis produces extremely robust results (Clarke et al., 2006). Figure 5-10 shows that the James and Ouse reference sites contain a spread of data while the Ouse regulated reaches have a greater degree of clustering. In re-examining the standard error graphs in Figure 5-9a-d, it can be seen from the groups with a smaller size class that there is a growing trend in variability for the Ouse regulated. That is, Figure 5-9a shows a smaller variability between sites for the Ouse regulated than Figure 5 4d shows for the Ouse regulated. These same trends to not extend to the unregulated Ouse and James River sites, as the results appear more random between sites. This indicates a degree of sorting in the Ouse regulated sites. The reasons behind the dominant differences were explored using SIMPER dissimilarity percentages index (). These showed that the dominant (~50 %) cause of the differences between sites was the variability, or in the case of the Ouse regulated reach, the lack of variability in the quantity of small gravel (4-25 mm). This result confirms the above conclusion that sorting of the fine sediment (small gravel up to small cobble) is occurring in the Ouse regulated sites. Sorting appears to diminish in the large cobbles with an x-axis greater than 225 mm (Figure 5-9f). These large cobbles are also likely to represent the immobile sediment within the stream bed, although flow duration curves would be required to determine the mobility of individual grains at a given discharge with the BAGS software (Pitlick et al., 2009).

Past studies that have considered the downstream impacts of dam construction have largely considered the hydrology (Garcia et al., 2010; Zimmerman et al., 2009), geology (Grant, 2003), ecology (Walker, 1985), physical responses (Brandt, 2000; Leopold et al., 1992), fine sediments of <4 mm (Bond, 2004) or a combination of these approaches (Petts and Gurnell, 2005;

Gordon et al., 2004). There have been limited studies in regulated gravel-cobble-boulder bedded streams that focus on the downstream changes to sediment composition or which have involved upstream-downstream comparisons. The regulation of these hard substrate streams has identified that more subtle alterations tend to occur, than in their alluvial counter-parts (Petts and Gurnell, 2005; Brandt, 2000; Leopold et al., 1992).

Headwater systems are important in river basins as they can provide up to 75 % of the river's sediment load and are the primary sediment source for the catchment through hillslope-channel sediment transition (Petts and Gurnell, 2005). The present study has shown that all the sub-catchments exhibit variability of sediment in the stream bed but that it is the spread and variability of this sediment inter-site that distinguishes the regulated site from the reference sites, where a large degree of variability is present (Figure 5-10).

In a separate study Sear (1995) found that in a river regulated by hydro-peaking (rapid rise fall in river level from power station discharge) over the past 12 years, changes in stream morphology were subtle. These included degradation of riffles suitable for spawning, development of fine sediment berms along channel margins, aggradation in pools, vegetative stabilisation of gravel bars and sediment accumulation in tributary confluences (Sear, 2005). The sediment composition showed a higher percentage of fines in the gravels and a general coarsening and armouring of the surface layer (Sear, 2005).

The results of the present study are consistent with the findings of Sear (2005) in that fines were located at all regulated sites in a similar abundance, while the reference sites showed a large variability between sites (i.e. some sites contained fewer small gravels but were off-set by containing medium gravels, as with the Ouse reference sites Figure 5-9a and b). Sear (2005) also noted that pools were in-filling (aggrading) and while it is not possible to determine the pre-dam depth of pools within the regulated reaches in the current study, there appeared, at least qualitatively, to be a distinct lack of deep pools at the regulated sites. Pools are required by fish and other vertebrates as refugia providing relief during summer conditions where regulation may limit flows during delicate life stages (Garcia et al., 2010).

The Ouse River downstream of Augusta Dam has previously been assessed to determine impacts on macroinvertebrate communities caused by flow regulation over the period 1983-1993 by Davies and Cook (1999) and one of the sites utilised in their study aligns with the current study area. Their study found that despite regulation there was no significant impact on macroinvertebrate community composition (Davies and Cook, 1999). This study suggested that it is likely the inflowing tributaries, occurring only a short distance downstream of the dam wall, mitigate the impact of the full diversion of flows, at least at the family level of macroinvertebrate community presence-absence and rank abundance (Davies and Cook, 1999). In addition to tributaries, sediment re-entering the channel is also highly likely to occur due to the overland spill events over the Augusta Dam spillway that occur most winters and which strip sediment from the Augusta Road and derive other sediment by overland flow before entering the regulated reaches of the Ouse River.

These results indicate that while the sediment downstream of Augusta Dam has been sorted in the small gravel to medium cobble range (Figure 4-4), shown by a clustering in the sediment size class distributions through the sites (Figure 5-10), new sediment is entering the regulated reaches. It is likely that most of this new sediment is likely to be entering from adjoining tributaries and from the Augusta Dam spillway flow path. As the channel bed sediments have been sorted through the regulated reaches of the Ouse River, which have received discharge flows for close to 60 years it is unlikely that this downstream environment would benefit from a flow aimed at mobilising sediment into a less sorted arrangement (more poorly sorted as in the reference reaches). This is due to the facts that:

a) The present dam outlets limit the pass-through of sediment and are likely to be insufficient to deliver the volumes of flow required to mobilise the coarser grained material;
b) Augusta Dam spillway is already likely to re-deliver some sediment to the regulated reaches of the Ouse River along with flows capable of mobilising the large gravel to small cobble sediment groups; and
c) The regulated reaches of the Ouse River are already sorted and adjusted to nearly 60 years of operation, thus any shorter-term flow releases are unlikely to significantly influence the sediment composition or deliver the flows required to scour deep pools – if any of these were actually present prior to dam construction.

Rather, future water transfers from Lake Augusta should target the ecological processes that have adapted to the past ~60 years of water transfers. This might be achieved through a Habitat Simulation or Hydraulic Rating flow (Section 2.4), so that the relatively natural range of macroinvertebrates communities that have been recorded downstream from the dam are maintained. This may be best achieved by allowing, where possible, the seasonal variation in river flows from the James and Ouse Rivers into Augusta Dam to be released downstream of the dam, particularly during summer when flow downstream of the dam may cease due to no releases from Augusta Dam. During winter typical spillway overtopping should be allowed to continue as this is likely to deliver the volume of flow into the Ouse River that would have occurred pre-dam and, additionally, will deliver new sediment downstream of Augusta Dam as is currently occurring.

6.3 Bedload transport

The Bedload Assessment for Gravel-bed Streams (BAGS) software was used to determine what rates of sediment transport were occurring within the upper Ouse River Catchment and associated sub-catchments. Thus the aim was to determine whether any differences in sediment transport occurred between sub-catchments or inter-site. Data inputs from the current study were utilised, which included the channel cross-section, a reach average channel-bed slope, discharge, grain size distribution and an estimate of Manning's *n*. The results shown in Table 5-7 and Table 5-8 indicates a very low rate of bedload transport, but with a distinct trend in higher mean sediment sizes at the bottom sites and lower mean sizes at the top sites. Normalised shear stress are higher at the top sites and lower at the bottom sites. This is consistent with the higher transport at the tops sites compared to the lower sites.

The over-all low rate of transport indicated by these results (Table 5-7) essentially confirms field observations made at the reference sites, which showed the presence of lichen that would normally be abraded from the rocks, grasses amongst gravel bars that would normally be removed and a complete lack in any high flow deposits on the stream margins or floodplains. The Ouse regulated sites are subject to greater flow velocities (Figure 5-4) than either of the reference sites (Table 5-2) and there was a marginally higher gradient (in the order of 0.001°); however, there is generally less fine sediment currently present in the Ouse River regulated reach. Sediments within these regulated reaches are typically more embedded (Table 5-1) and there is likely to have been a greater amount of past bedload transport associated with the previous ~60 years of dam operations than is presently the case. The coarse grade sediment eroded from within the channel margins has not been replenished due to the presence of Augusta Dam and only fine grained transport is likely to be associated with adjoining tributaries that re-deliver fine sediment downstream of the dam wall, but are not able to mobilise sediment the large gravel to medium cobble range (Figure 4-4). However larger sediment may possibly be input from the Augusta Dam spillway flow path.

The results in Table 5-7 indicate the range of low but variable rates that can be expected when computing of bedload movement in low-gradient headwater streams, depending on the equation utilised. Essentially the data shows that the relationship of low gradient, low flows in a headwater environment, combined with a flat box-shaped stream inhibit the transport of sediment to downstream environments. However, when comparing the transport rates of Table 5-7 with the shear stress (τ) values and grain size means (+/- one standard mean) of Table 5-8, it becomes clear that sediment at the upstream sites has a smaller mean diameter (x-axis) and a greater τ value that results in an increase, albeit minor, in sediment transport. Conversely the downstream increase in grain size x-axis corresponds with a higher τ value, which results in less bedload being transported. This finding was true for all three sub-catchments for the most upstream and downstream sites respectively indicating that shear stress and grain size may be a good indicator of potential bedload transport.

The downstream decrease in shear stress with corresponding deposition is consistent with the findings of Montgomery and Buffington (1997, in Gordon et al., 2004), who found that τ values in the order of 0.20 equated with areas of debris flow dominated colluvial and cascade material; while, τ values of ~0.10 were associated with step-pool environments on the fringe of the scour and deposition threshold. In a different study comparing sediment transport in pool-riffle environments Sear (1996) found that sediment transport varied at the local scale depending on the τ value. In pool environments Sear (1996) found that a lower range of τ values were required before sediment in pools became mobilised; conversely riffle environments required a wide shear stress range before bed mobility occurred. This is thought to be because of the trapping efficiency of individual grains being greater in riffle environments, where fine sediment may become trapped behind coarser grade sediment (Sear, 1996). Sear (1996) concluded that it was because this efficient trapping of sediments was not as apparent in pool environments that lower shear stresses were required to initiate grain motion.

In another study on the relationship between shear stress and bedload transport on an outer meander bend Clayton and Pitlick (2007) found that shear stress was greater on the outer bend while the inner bend had lower τ values. In this way coarse sediment was transported to the outer bend where it was more efficiently transported with greater shear stress exerted, while fine sediment was shifted to the inside bend where comparatively less shear stress occurred. The results of this study found that through this sorting of the sediment within the stream bend and the variable shear stress, although sediment was transported in different areas of the bend, roughly the same total quantity of the full range of sediment sizes were transported, thus balancing the total sediment transport (Clayton and Pitlick, 2007).

In a study of a low-land alluvial stream, Pipers River, in Tasmania, Locatelli (2001) found that stream power was more responsible for erosion rates being observed ($r^2=0.9$), than bankfull discharge or shear stress. However, being an alluvial stream with a greater catchment area, the difference in findings to that of an alpine cobble-boulder bed river in the current study may be a result of the geographical settings. Regardless, the current study has shown that alpine low gradient streams show a direct relationship between sediment transport and shear stress, at least empirically. Furthermore, the above studies highlight that local variability with grainsize and shear stress may occur and that this is dependent on reach-scale geomorphic units (Clayton and Pitlick, 2007; Montgomery and Buffington 1997, in Gordon et al., 2004; Sear, 1996). The empirically based sediment transport equations of this study do not consider the presence of Augusta Dam upstream of the regulated sites. However, this alteration is already factored into the input data, as actual sediment distributions from the field data at the regulated sites were used in the bedload transport equations. The quality of the sediment transport rates revealed by this study could be improved in the future by utilising a rating curve for the hydrological input, calculating Manning's *n* through a 1D model such as HEC RAS and obtaining a reach-average water level slope instead of bed-average from a DEM. The use of a rating curve would allow the model to determine the individual grain sizes that become mobile at a given discharge; as opposed to only bedload quantities that were determined in this study from a single discharge/gauging record. This information may also assist in understanding the process of sorting downstream of Augusta Dam.

Chapter 7 Conclusion

The upper Ouse River catchment represents a legacy of geological substrate, weathering, glaciation, fluvial processes, and anthropogenic catchment modifications. Current awareness of the importance that geomorphological processes have had on this region have led to its incorporation into the TWWHA. This study has investigated the fluvial geomorphology of the Ouse River at regulated sites downstream of Augusta Dam and compared these quantitatively with the James and Ouse River sites that enter Lake Augusta further upstream. The three areas of investigation formed sub-catchments and eight sites were selected within each sub-catchment, giving a total of 24 sites.

Quantitative comparisons were made by sampling the surface sediment at each of the 24 sites using digital grain identification software Digital Gravelometer™, which produced grain size distributions and provided raw data on individual grain sizes that were grouped into standard classes. The statistical analysis of the results showed that reference sites varied significantly for small gravels (4-25 mm) and the James reference sites varied significantly from the Ouse regulated sites for small gravels4-25 mm, large gravels (51-75 mm) and small cobbles (76-150 mm) as shown in Table 5-4). Although the Ouse reference and regulated sites were not significantly different statistically, there was consistently more variability in the sediment composition in the reference sites. This variation was clearly and robustly shown in an MDS ordination plot of all sites (Figure 5-10) that identified clustering in the Ouse regulated sites indicating lower variability between each of the regulated sites, compared with a greater variability in the reference sites.

Bedload transport was calculated for upstream and downstream sites in all three sub-catchments using the BAGS software and indicated very low rates of sediment transport in the catchment. Larger rates of sediment movement were calculated for all upstream sites compared to the downstream sites, which showed a direct relationship between a high normalised shear stress value at upstream sites and low values for downstream.

The regulated sites exhibit a degree of sorting that has occurred due to the presence of a dam further upstream that limits sediment pass-through to the downstream sites. New sediment is predicted to continue to enter the regulated sites from adjoining tributaries and through the Augusta Dam spillway that flows over Augusta Road and continues overland via an ill-defined channel from which it collects and delivers new sediment to the regulated reach of the Ouse River. The sediment sorting present at the regulated sites is not present at upstream sites and indicates the subtle changes that have occurred in this relatively robust catchment where colluvial material with step-pool and riffle-pool-run sections dominate.

These results indicate the nature of the subtle changes to river channel morphology that have occurred after nearly 60 years of river regulation in a gravel-cobble-boulder dominated river. The current operation of Augusta Dam creates hydrologically hostile flow for sediment retention and ecological life in the downstream environment to which sediment in the Ouse River has adjusted and continues to respond. Rather than the Ouse River being rendered devoid of fine material in the sites downstream of Augusta Dam, fine sediment replenishment is currently received through tributaries and the discharge downstream from the Augusta Dam spillway. On this basis, an environmental flow aimed at redistributing sediment downstream of Augusta Dam to improve ecological health would seem ill-advised. In part, this is also due to the Ouse River having since adjusted to a new equilibrium after nearly 60 years of dam operations. Rather, future management of water releases from Augusta Dam should, where practical, focus on discharging water in summer based on natural upstream summer in-flows and in winter to allow flows that currently over-top the spillway to continue, because these flows account for some high winter flow variability that would have occurred pre-dam. Additionally, spill events from the Augusta Dam spillway aid the delivery of new sediment to the Ouse River downstream of Augusta Dam.

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Appendix A

Site naming and coordinates

Ouse River Study Sites			James River Study Sites			Ouse River Reference Sites		
	Easting	Northing		Easting	Northing		Easting	Northing
OS1	0464683	5366615	J1	0456069	5369815	OR1	0460240	5370784
OS2	0464700	5366105	J2	0456204	5369721	OR2	0460252	5370717
OS3	0464618	5365942	J3	0456403	5369371	OR3	0460633	5370302
OS4	0465439	5364825	J4	0456482	5369248	OR4	0461313	5370212
OS5	0466485	5363420	J5	0456465	5369223	OR5	0461344	5370194
OS6	0466605	5363088	J6	0456428	5368814	OR6	0461493	5370116
OS7	0466990	5362696	J7	0456479	5368657	OR7	0461654	5369718
OS8	0461906	5369488	J8	0457785	5367921	OR8	0468450	5361133

Appendix B

Image Ratings from Digital Gravelometer

Site	Photo Number(s)	Visual Match (1 poor - 10 good)	Truncation (mm)
OS1	IMG_3536_OS1.JPG	6	8.7
OS1	IMG_3537_OS1.JPG	7	8.7
OS1	IMG_3539_OS1.JPG	5	8
OS2	IMG_3512_OS2.JPG	6	8
OS2	IMG_3514_OS2.JPG	7	7.8
OS2	IMG_3517_OS2.JPG	8	8.5
OS3	IMG_3520_OS3.JPG	9	8.6
OS3	IMG_3525_OS3.JPG	7	9.3
OS3	IMG_3529_OS3.JPG	8	7.9
OS4	IMG_3546_OS4.JPG	5	8.2
OS4	IMG_3547_OS4.JPG	4	8.6
OS4	IMG_3549_OS4.JPG	7	7.4
OS5	IMG_3643_OS5.JPG	5	9
OS6	IMG_3655_OS6.JPG	5	8.4
OS7	IMG_3630_OS7.JPG	8	8.1
OS7	IMG_3636_OS7.JPG	5	8
OS7	IMG_3638_OS7.JPG	7	8.4
OS8	IMG_3665_OS8.JPG	4	9
OS8	IMG_3666_OS8.JPG	5	13.6
J1	IMG_0537_James_1.JPG	6	8.2
J1	IMG_0538_James_1.JPG	2	n/a
J2	IMG_0536_James_2.JPG	7	8.2
J2	IMG_0535_James_2.JPG	8	8
J3	IMG_0534_James_3.JPG	5	8.2
J4	IMG_0523_James_4.JPG	8	8.1
J4	IMG_0522_James_4.JPG	9	8.1
J4	IMG_0521_James_4.JPG	8	8
J5	IMG_0513_James_5.JPG	9	6.9
J5	IMG_0517_James_5.JPG	9	7.9
J5	IMG_0519_James_5.JPG	9	8
J6	IMG_0511_James_6.JPG	4	9.8
J6	IMG_0507_James_6.JPG	5	7.4
J7	IMG_0504_James_7.JPG	8	7.9

Site	Photo Number(s)	Visual Match (1 poor - 10 good)	Truncation (mm)
J7	IMG_0502_James_7.JPG	9	7.3
J8	IMG_0494_James_8.JPG	7	7.9
J8	IMG_0490_James_8.JPG	5	7.6
J8	IMG_0489_James_8.JPG	6	7.2
J8	IMG_0486_James_8.JPG	2	n/a
OR1	IMG_0540_Ouse 1.JPG	8	8
OR1	IMG_0543_Ouse 1.JPG	7	7.7
OR1	IMG_0544_Ouse 1.JPG	8	8.1
OR2	IMG_0548_Ouse 2.JPG	6	7.7
OR2	IMG_0552_Ouse 2.JPG	8	8.4
OR3	IMG_0835_Ouse 3.JPG	5	8.4
OR4	IMG_0836_Ouse 4.JPG	7	8.2
OR4	IMG_0837_Ouse 4.JPG	7	8.3
OR5	IMG_0838_Ouse 5.JPG	8	8.3
OR5	IMG_0839_Ouse 5.JPG	1	n/a
OR5	IMG_0840_Ouse 5.JPG	5	8.4
OR6	IMG_0841_Ouse 6.JPG	3	n/a
OR6	IMG_0842_Ouse 6.JPG	6	8.2
OR7	IMG_0846_Ouse 7.JPG	5	8.4
OR8	IMG_0854_Ouse 8.JPG	5	10.5

Appendix C

Example of a Physical Form Data Sheet

AUSRIVAS Physical Assessment Protocol Field Data Sheets Page 1 Site ouse 01/02 Date 22/02/09

Date 22/2/09 Site No. 01/02 Time 1540 DST Recorder's Name DAX / LUKAS

River Name Ouse Rv - Top Location Top - Upper catchment

Weather sunny / cloudy 45% Rain in last week? Y [✓] N [ ]

Latitude: deg min sec Longitude: deg min sec

GPS Name and Datum ouse 01 E 460240 N 5370784 02 E 460252 N 5370717

Photograph numbers and details

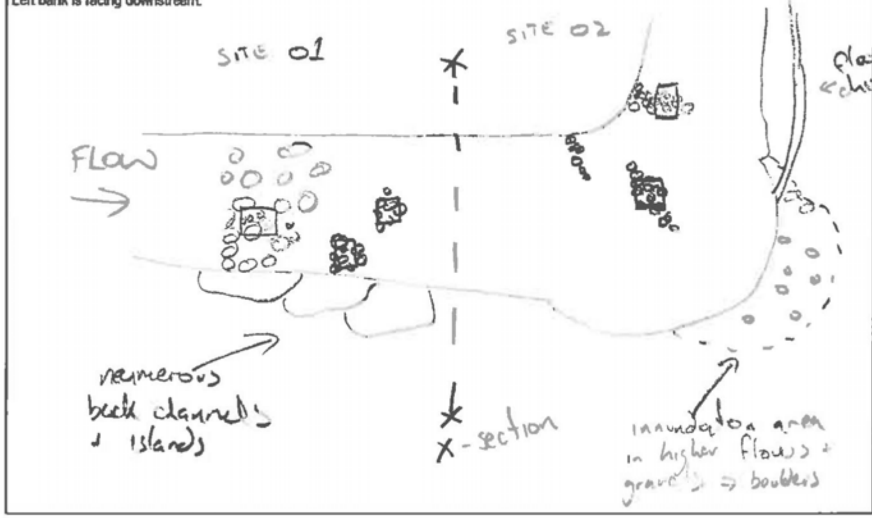
ouse 01 100 - 0539 → 100 - 544

ouse 02 100 - 545 → 100 - 552

PLANFORM SKETCH OF SITE

Including bedform types, location of cross-sections, access points, landmarks and natural or artificial channel or floodplain features.

Left bank is facing downstream.



Notes

BEFORE LEAVING THE SITE, CHECK DATA SHEETS TO ENSURE THAT ALL VARIABLES HAVE BEEN RECORDED ☐ Y

Acknowledgments - The content and layout of these data sheets are derived from the sheets used in the River Habitat Audit Procedure (Anderson, 1993a), AUSRIVAS, the Index of Stream Condition (Ladson and White, 1999 and DNRE Victoria) and the River Habitat Survey (Raven *et al.*, 1998).

AUSRIVAS Physical Assessment Protocol Field Data Sheets **Page** **Site** ________ **Date** ____________

Notes

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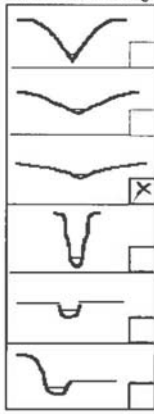
Valley shape
Choose one category only



Valley shape	
[ ]	Steep valley
[ ]	Shallow valley
[x]	Broad valley
[ ]	Gorge
[ ]	Symmetrical floodplain
[ ]	Asymmetrical floodplain

Local impacts on streams
Choose one or more categories and describe the detail of each

- [ ] Sand or gravel mining
- [ ] Other mining
- [ ] Road
- [ ] Bridge / culvert / wharf
- [ ] Ford / ramp
- [ ] Discharge pipe
- [ ] Forestry activities
- [ ] Sugar mill
- [ ] Irrigation run-off or pipe outlet
- [ ] Sewage effluent
- [ ] Channel straightening
- [ ] River improvement works
- [ ] Water extraction
- [ ] Dredging
- [x] Grazing
- [ ] Litter
- [ ] Recreation
- [x] Other

Description ______________________________

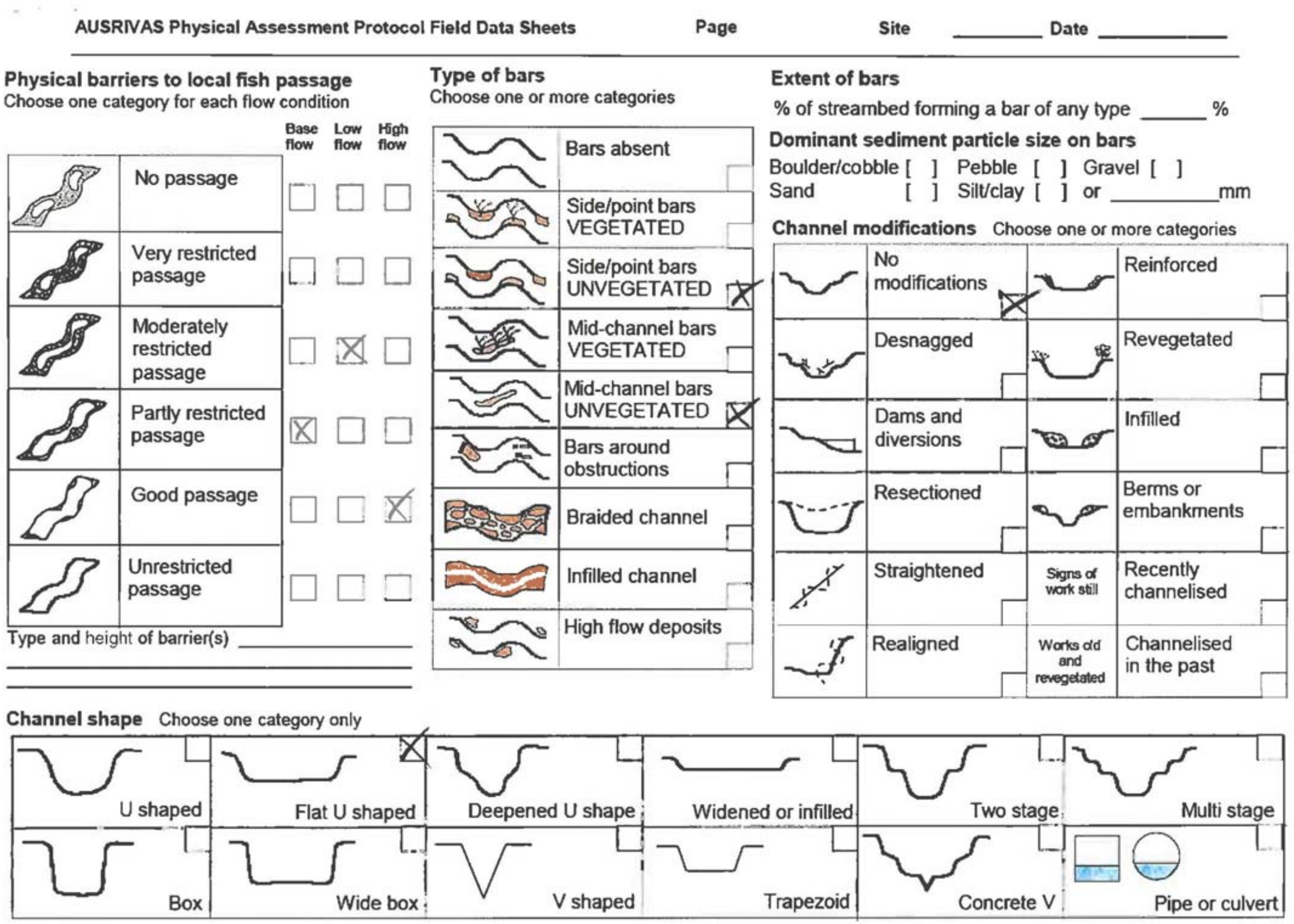
Floodplain width ____ ____ ____ Average ____ (m)

Floodplain features
Choose one or more features when present

- [ ] Sampling site has no distinct floodplain
- [ ] Oxbows / billabongs
  Body of water occupying a former river meander, isolated by a shift in the stream channel
- [x] Remnant channels
  Formed during a previous hydrological regime. May be infilled with sediment
- [x] Flood channels
  A channel that distributes water onto the floodplain and off the floodplain during floods
- [ ] Scroll systems
  Short, crescentic strips or patches formed along the inner bank of a stream meander
- [ ] Splays
  Small alluvial fan formed where an overloaded stream breaks through a levee and deposits material on the floodplain
- [x] Floodplain scours
  Scour holes formed by the concentrated clearing and digging action of flowing water
- [ ] No floodplain features present
  Floodplain present at the sampling site but does not contain any of the above features

Local landuse
Choose one category for each bank

Left	Right	
[x]	[x]	Native ~~forest~~
[ ]	[ ]	Native grassland (not grazed)
[ ]	[ ]	Grazing (native or non-native pasture)
[ ]	[ ]	Exotic grassland (lawns etc., no grazing)
[ ]	[ ]	Forestry Native [ ][ ] Pine [ ][ ]
[ ]	[ ]	Cropped Rainfed [ ][ ] Irrigated [ ][ ]
[ ]	[ ]	Urban residential
[ ]	[ ]	Commercial
[ ]	[ ]	Industrial or intensive agricultural
[ ]	[ ]	Recreation
[ ]	[ ]	Other ____________



AUSRIVAS Physical Assessment Protocol Field Data Sheets　　Page　　Site ________ Date ____________

Physical barriers to local fish passage
Choose one category for each flow condition

	Base flow	Low flow	High flow
No passage	☐	☐	☐
Very restricted passage	☐	☐	☐
Moderately restricted passage	☐	☒	☐
Partly restricted passage	☒	☐	☐
Good passage	☐	☐	☒
Unrestricted passage	☐	☐	☐

Type and height of barrier(s) ____________________

Type of bars
Choose one or more categories

Bars absent	☐
Side/point bars VEGETATED	☐
Side/point bars UNVEGETATED	☒
Mid-channel bars VEGETATED	☐
Mid-channel bars UNVEGETATED	☒
Bars around obstructions	☐
Braided channel	☐
Infilled channel	☐
High flow deposits	☐

Extent of bars
% of streambed forming a bar of any type ______ %

Dominant sediment particle size on bars
Boulder/cobble [ ] Pebble [ ] Gravel [ ]
Sand [ ] Silt/clay [ ] or __________ mm

Channel modifications Choose one or more categories

No modifications	☒		Reinforced	☐
Desnagged	☐		Revegetated	☐
Dams and diversions	☐		Infilled	☐
Resectioned	☐		Berms or embankments	☐
Straightened	☐	Signs of work still	Recently channelised	☐
Realigned	☐	Works old and revegetated	Channelised in the past	☐

Channel shape Choose one category only

U shaped ☐	Flat U shaped ☒	Deepened U shape ☐	Widened or infilled ☐	Two stage ☐	Multi stage ☐
Box ☐	Wide box ☐	V shaped ☐	Trapezoid ☐	Concrete V ☐	Pipe or culvert ☐

AUSRIVAS Physical Assessment Protocol Field Data Sheets Page Site ________ Date __________

Bank shape
Choose one category for each bank

		Left bank	Right bank
	Concave	☐	☐
	Convex	☐	☐
	Stepped	☒	☒
	Wide lower bench	☐	☒
	Undercut	☐	☐

Factors affecting bank stability
Choose one or more categories

- ☒ None
- ☐ Mining
- ☐ Runoff
- ☐ Stock access
- ☐ Human access
- ☐ Ford, culvert or bridge
- ☐ Feral animals
- ☒ Other
- ☐ Cleared vegetation
- ☐ Irrigation draw-down
- ☐ Reservoir releases
- ☐ Seepage
- ☐ Flow and waves
- ☐ Drainpipes

Description native grazing + wombats

Bank slope
Choose one category for each bank

		Left bank	Right bank
	Vertical 80 - 90°	☐	☒
	Steep 60 - 80°	☒	☐
	Moderate 30 - 60°	☐	☐
	Low 10 - 30°	☐	☐
	Flat <10°	☐	☐

Bedrock outcrops
Assess % of each bank covered by bedrock outcrops

% bedrock outcrops Left bank ______
Right Bank ______

Artificial bank protection measures
Choose one or more categories

- ☒ None
- ☐ Fence structures
- ☐ Levee banks
- ☐ Rock or wall layer
- ☐ Rip rap
- ☐ Fenced human access
- ☐ Other ____________
- ☐ Fenced stock watering points
- ☐ Vegetation plantings
- ☐ Logs strapped to bank
- ☐ Concrete channel lining

Sediment oils
☒ absent ☐ light ☐ moderate ☐ profuse

Water oils
☒ none ☐ flecks ☐ globs ☐ sheen ☐ slick

Sediment odours
☒ normal/none ☐ sewage ☐ petroleum ☐ chemical
☐ anaerobic ☐ other ____________

Water odours
☒ normal/none ☐ sewage ☐ petroleum ☐ chemical
☐ other ____________

Turbidity (visual assessment)
☒ Clear ☐ Slight ☐ Turbid ☐ Opaque

Is water clarity reduced by:
☐ Suspended material (e.g mud, clay, organics) ☐ Dissolved material (e.g plant leachates)

Water level at the time of visual assessment
☐ Dry ☐ No flow ☒ Low ☐ Baseflow or near baseflow
☐ High ☐ Flood (don't sample)

Artificial features at the sampling site
Choose one or more categories

☐ Major ☐ Minor weir ☐ Ford ☐ Bridge ☐ Culvert ☐ Other

Description ____________

Large woody debris
Overall % cover of logs and branches greater than 10cm in diameter

______% Notes on visibility ____________

AUSRIVAS Physical Assessment Protocol Field Data Sheets Page Site ________ Date ____________

Bed compaction
Choose one category only

Category	Description
Tightly packed, armoured	Array of sediment sizes, overlapping, tightly packed and very hard to dislodge
Packed, unarmoured	Array of sediment sizes, overlapping, tightly packed but can be dislodged with moderate
Moderate compaction	Array of sediment sizes, little overlapping, some packing but can be dislodged with moderate
Low compaction (1)	Limited range of sediment sizes, little overlapping, some packing and structure but can be dislodged very easily
Low compaction (2)	Loose array of fine sediments, no overlapping, no packing and structure and can be dislodged very easily

Sediment matrix
Choose one category only

Category	Description
Bedrock	
Open framework	0-5% fine sediment, high availability of interstitial spaces
Matrix filled contact framework	5-32% fine sediment, moderate availability of interstitial spaces
Framework dilated	32-60% fine sediment, low availability of interstitial spaces
Matrix dominated	>60% fine sediment, interstitial spaces virtually absent

Sediment angularity
Choose one category only
Assess cobble, pebble and gravel fractions only

Category
Very angular
Angular
Sub-angular
Rounded
Well rounded
Cobble, pebble and gravel fractions not present

In the USEPA Habitat Assessment on the following pages, be sure to use the correct form for high or low gradient streams

Bed stability rating
Choose one category only

Unstable - eroding ← Stable → Unstable - depositing

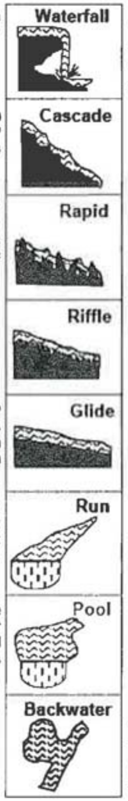
Severe erosion	Moderate erosion	Bed stable	Moderate deposition	Severe deposition
Streambed scoured of fine sediments. Signs of channel deepening. Bare, severely eroded banks. Erosion heads. Steep streambed caused by erosion.	Little fine sediment present. Signs of channel deepening. Eroded banks. Streambed deep and narrow. Steep streambed comprised of unconsolidated (loosely arranged and unpacked) material	A range of sediment sizes present in the streambed. Channel is in a 'relatively natural' state (not deepened or infilled). Bed and bar sediments are roughly the same size. Banks stable. Streambed comprised of consolidated (tightly arranged and packed) material.	Moderate build-up of fine sediments at obstructions and bars. Streambed flat and uniform. Channel wide and shallow.	Extensive build up of fine sediments to form a flat bed. Channel blocked, but wide and shallow. Bars large and covering most of the bed or banks. Streambed comprised of unconsolidated (loosely arranged and unpacked) material.

AUSRIVAS Physical Assessment Protocol Field Data Sheets

Page Site ________ Date ____________

Extent of bedform features

Total % composition for all features must equal 100%



Description	Feature	Value	Measure
Height >1m, Gradient >60°	Waterfall	____	% of site
		____	Est. Av. Length (m)
		____	Est. Av. Height (m)
		____	Est. Av. Gradient (°)
Step Height <1m, Gradient 5-60°, Strong currents	Cascade	____	% of site
		____	Est. Av. Length (m)
		____	Est. Av. Height (m)
		____	Est. Av. Gradient (°)
Gradient 3-5°, Strong currents, Rocks break surface	Rapid	____	% of site
		____	Est. Av. Length (m)
		____	Est. Av. Depth (m)
		____	Est. Av. Width (m)
Gradient 1-3°, Moderate currents, Surface unbroken but unsmooth	Riffle	10	% of site
		20	Est. Av. Length (m)
		0.10	Est. Av. Depth (m)
		15	Est. Av. Width (m)
Gradient 1-3°, Small currents, Surface unbroken and smooth	Glide	____	% of site
		____	Est. Av. Length (m)
		____	Est. Av. Depth (m)
		____	Est. Av. Width (m)
Gradient 1-3°, Small but distinct & uniform current, Surface unbroken	Run	____	% of site
		____	Est. Av. Length (m)
		____	Est. Av. Depth (m)
		____	Est. Av. Width (m)
Area where stream widens or deepens and current declines	Pool	90	% of site
		100	Est. Av. Length (m)
		0.30	Est. Av. Depth (m)
		15	Est. Av. Width (m)
A reasonable sized (>20% of channel width) cut-off section away from	Backwater	____	% of site
		____	Est. Av. Length (m)
		____	Est. Av. Depth (m)
		____	Est. Av. Width (m)

Note: An additional response variable <u>planform channel pattern</u> is measured in the office

Bank material

Assess % composition for each bank

	Left bank	Right bank
Bedrock	____	____
Boulder (>256mm)	____	____
Cobble (64-256mm)	____	____
Pebble (16-64mm)	____	____
Gravel (2-16mm)	____	____
Sand (0.06-2mm)	____	____
Fines (silt and clay, <0.06mm)	____	____

Total 100% each

Substrate composition

Assess % composition in the area of bed 5m either side of the cross-section.

Bedrock	____
Boulder (>256mm)	____
Cobble (64-256mm)	____
Pebble (16-64mm)	____
Gravel (2-16mm)	____
Sand (0.06-2mm)	____
Fines (silt and clay <0.06mm)	____

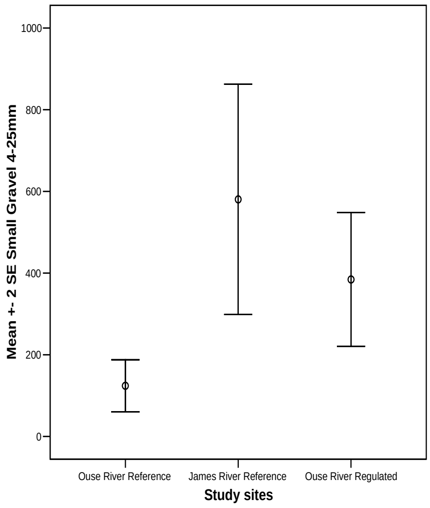
Total 100%

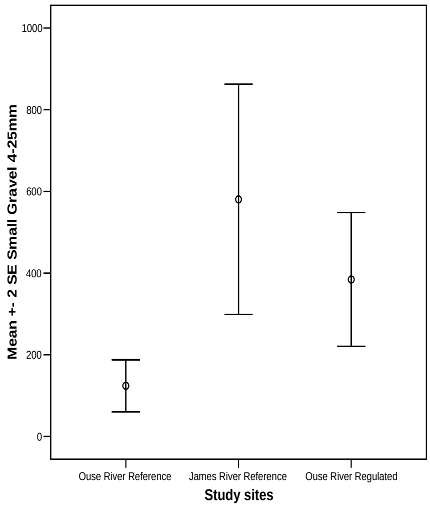
Notes / sketch

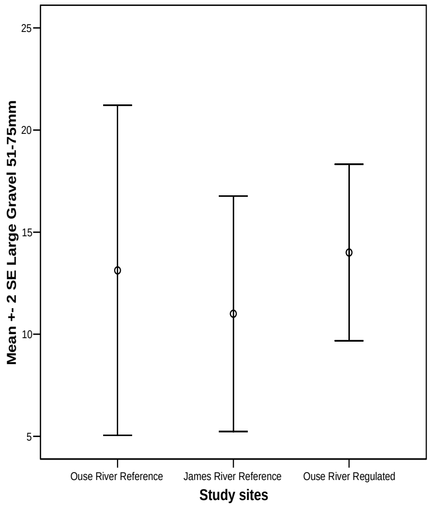
Appendix D

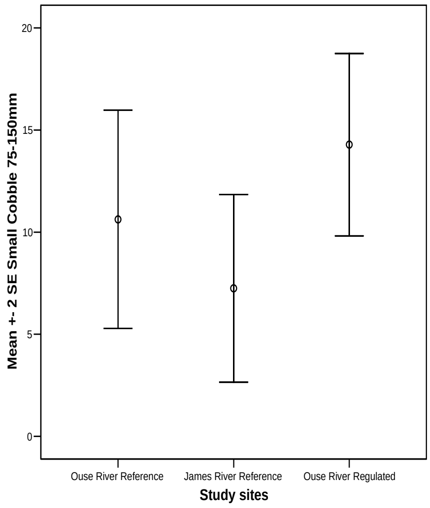
Statistical Analysis on Best Individual Image Only for Each Site

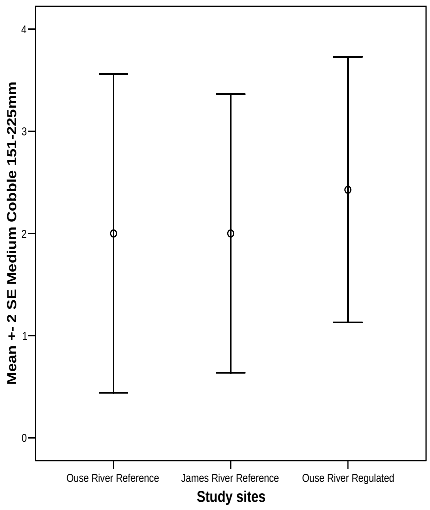
Standard Error by Sediment Size Class for Sites 1-8 all Sub-Catchments



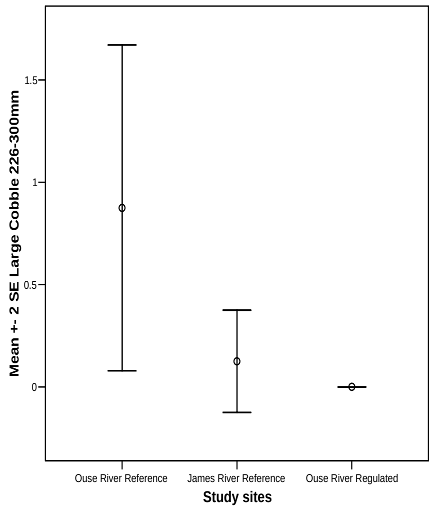




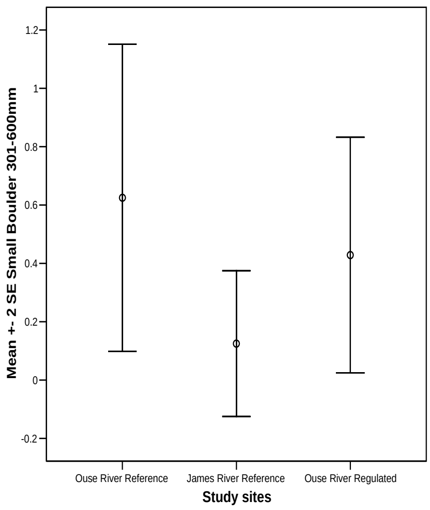




Mean +- 2 SE Medium Cobble 151-225mm
0
1
2
3
4
Ouse River Reference
James River Reference
Ouse River Regulated
Study sites



Mean +- 2 SE Large Cobble 226-300mm
0
0.5
1
1.5
Ouse River Reference
James River Reference
Ouse River Regulated
Study sites



Mean +- 2 SE Small Boulder 301-600mm
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
Ouse River Reference
James River Reference
Ouse River Regulated
Study sites